# Report of the NSAC Subcommittee on Low Energy Nuclear Physics

November 15, 2001

# Contents

# 1 Executive Summary

In July 2001, the Department of Energy (DOE) and the National Science Foundation (NSF) charged the Nuclear Science Advisory Committee (NSAC) to review and evaluate the scientific opportunities and priorities within the DOE Low Energy Nuclear Physics Program. The charge specifically focussed on the nuclear structure and nuclear astrophysics component of this sub-field and the three national laboratory facilities and four university facilities that are operated under this program. In response to its charge, NSAC formed a subcommittee to review the facilities and evaluate the scientific opportunities and priorities of this program.

The subcommittee gained a detailed understanding of this program, based on site visits to the facilities and additional input from the DOE, the facilities, and the low energy nuclear physics community. The subcommittee also endorsed the recommendations of the 2001 Long-Range Plan for nuclear physics. This input led the subcommittee to its primary finding:

- **The Low Energy Nuclear Physics Program is carrying out an outstanding program of high impact science with exciting directions for the future, but is presently handicapped by a funding shortfall that threatens to undermine its recent progress**

The subcommittee confirms that the field is pursuing first-rate science; it is highly productive and there are promising directions for the future. In particular, a large fraction of the low energy nuclear physics research community is on an exciting research path that will lead to the next-generation facility for producing accelerated beams of radioactive ions. This Rare Isotope Accelerator (RIA) has been given the highest priority for major new construction in the FY01 NSAC Long Range Plan.

However the DOE Low Energy Nuclear Physics Program is also facing severe budgetary pressures. Funding levels at all of the facilities are significantly below what is needed for full utilization. In addition progress on new initiatives, in particular RIA, require increasing levels of funding that cannot be accommodated within the approximately constant funding levels that exist. Thus the subcommittee determined that the inability of the facilities supported by the program to operate at full potential, coupled with the importance of supporting new initiatives that represent the future of the field, has resulted in a wholly unsatisfactory situation for the low-energy nuclear physics community.

In its charge to NSAC, the funding agencies asked that the key opportunities and capabilities in low energy nuclear physics be identified not only within the DOE program but also in the NSF and non-US programs. The subcommittee, in response to this request, finds:

- **It is essential that the low energy nuclear physics community pursue a balanced program that combines effective utilization of its existing facilities with new opportunities within the US and abroad while continuing development of its future "flagship" facility, RIA.**

This includes effective utilization of the DOE facilities, continued support for RIA R&D and continued support for research at the universities and national laboratories.

In addition, the community has clearly identified that the exploration of structure and reactions involving radioactive nuclei far from the valley of stability represents a new frontier in our understanding of nuclear structure and nuclear astrophysics. However construction of RIA will likely take at least a decade, and a number of opportunities presently exist (or will soon) to pursue radioactive beam research. These include the HRIBF facility at Oak Ridge National Laboratory and the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory (CCF/NSCL) in the US, ISAC in Canada and other facilities in Japan and Europe. The subcommittee recommends that focused programs by US researchers at these facilities should be strongly supported. It is also essential to maintain sufficient capabilities in the production of stable beams of adequate intensity, energy and range of atomic mass to pursue the high quality physics program that presently exists and that will continue during the RIA era.

The subcommittee was also asked to prioritize the opportunities within the Low Energy Nuclear Physics Program under two different future funding scenarios: a constant effort budget (increases only for inflation) and a budget above constant effort. Within both budget scenarios the subcommittee identified a set of critical priorities.

- **Within a constant effort funding scenario severe changes in the program are necessary in order to address the key priorities of the Low Energy Nuclear Physics Program.**

These changes include termination of DOE support for operations at the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory (LBNL) and the tandem accelerator at the University of Washington. In addition, funding for Research and Development (R&D) of the Rare Isotope Accelerator (RIA) would be limited to a modest increase above present funding levels. These changes represent a substantial scientific loss as outlined in the body of this report.

Contrary to the significant scientific losses that would result from the constant effort scenario, additional funding for the DOE Low Energy Nuclear Physics Program would have profound impact for nuclear science:

- **Funding at a level about 15% above a constant effort budget, would lead to enormous opportunities for the fields of nuclear structure and nuclear astrophysics.**

Continued operation of the 88-Inch Cyclotron at LBNL would allow an outstanding program of heavy-element chemistry and nuclear physics, gamma-ray spectroscopy for nuclear structure, weak interaction studies, and development of a few specialized, high-intensity radioactive beams to be realized. Increased funding for RIA R&D would allow this forefront project to proceed towards a timely construction and permit the advancement of a number of performance-critical components in the project. Increased funding for the development of a new gamma-ray tracking detector would allow the unique capabilities of this detector to be exploited at existing stable and radioactive beam facilities. Restoration of operations at the UW tandem accelerator would allow the execution of key experiments in nuclear astrophysics and weak interactions. Lastly, needed increases in operations support for the facilities would allow the facilities to achieve optimum and effective utilization.

# 2 Introduction

Nuclear science, for the past twenty years, has considered the identification of long range goals for the field to be a high priority. This process has involved a series of planning exercises (approximately every six years) whereby the community looks within its varied research programs and identifies the critical priorities for the field. The process is coordinated by the Nuclear Science Advisory Committee (NSAC), a panel of nuclear science researchers that provides advice to the funding agencies that support nuclear science. In the very near future NSAC will submit the 2001 Long Range Plan (LRP) to the funding agencies. However the key recommendations and findings of the 2001 LRP exercise have already been presented and are being incorporated into the planning for future funding.

The highest priority of the 2001 LRP recommends increased funding for effective utilization of the existing nuclear physics facilities, while the second recommendation endorses the Rare Isotope Accelerator (RIA) as the next major construction project for the field. Both of these recommendations have significant impact on the subfields of nuclear structure and nuclear astrophysics, as this subfield operates a number of user and university facilities and because RIA's main scientific goals address questions in nuclear structure and nuclear astrophysics.

In July 2001, James Decker, Acting Director of the Department of Energy (DOE) Office of Science, and Robert Eisenstein, Assistant Director of Mathematical and Physical Sciences at the National Science Foundation (NSF), charged NSAC to review and evaluate the scientific opportunities and priorities within the Low Energy Nuclear Physics Program at DOE. The charge specifically focussed on the nuclear structure and nuclear astrophysics component of this subfield and the three national laboratory facilities and four university facilities that are operated under this program. At its meeting on July 23, 2001, NSAC discussed this charge and appointed a subcommittee to prepare a detailed analysis of the capabilities and opportunities in this subfield.

This subcommittee, chaired by Brad Filippone, consists of eight members from the nuclear research community. There are seven experimentalists and one theorist, including a representative from outside the US nuclear physics community. The membership of this subcommittee is shown in Appendix A. In addition to the subcommittee members, several members from the DOE Office of Science (Dennis Kovar, Director of the Division of Nuclear Physics; Gene Henry, Program Manager for Low Energy Nuclear Physics) and the NSF Nuclear Physics Program (Alice Mignerey and Sherry Yennello, University Rotators) were present at meetings of the subcommittee. NSAC Chairman James Symons also attended many of the meetings of the subcommittee.

Early in its deliberations the subcommittee identified research activities that should be included in the charge. The charge to NSAC requested that the report evaluate the capabilities of the existing nuclear structure and nuclear astrophysics facilities supported by the DOE Low Energy Nuclear Physics Program. These facilities are the Argonne Tandem Linear Accelerator System (ATLAS) at Argonne National Laboratory (ANL), the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory (LBNL), the Holifield Radioactive Ion Beam Facility (HRIBF) at the Oak Ridge National Laboratory (ORNL), the Cyclotron Institute at Texas A&M University (TAMU), the Triangle Universities Nuclear Laboratory (TUNL) comprised of Duke University, University of North Carolina and North Carolina State University, the Center for Experimental Nuclear Physics and Astrophysics (CENPA) at the University of Washington (UW) and the Wright Nuclear Structure Laboratory (WNSL) at Yale University. Based on the charge, the subcommittee (in consultation with representatives from the Division of Nuclear Physics at DOE) chose to focus on that research which is carried out at these facilities. Thus, in addition to nuclear structure and nuclear astrophysics, some programs exploring nuclear reactions of heavy ions at low to intermediate energies, fundamental interactions using radioactive nuclei and the interactions of few-body systems studied via low energy nuclear reactions were included in the review. Programs that investigate neutrino properties and neutrino astrophysics as well as fundamental interactions of neutrons, while partially funded through the Low Energy Nuclear Physics Program, were not included in the deliberations of the subcommittee.

As the subcommittee was appointed on August 20, 2001 and asked to deliver its report by November 15, 2001, time was a serious constraint on the deliberations of the subcommittee. Site visits by the full subcommittee were limited to the national laboratories, with the university facilities making presentations to the full subcommittee at a neutral site (Brookhaven National Laboratory - BNL). In addition, each of the university facilities was visited by a subset of the subcommittee. One subcommittee member also visited the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University.

Also, because of the limited time available, the subcommittee could not obtain a detailed understanding of the operations at the facilities. However, as the charge asked for a review of scientific opportunities and capabilities, the subcommittee believes that its findings, based on the input it received from the facilities, the community and the funding agencies, are thoughtful, robust and sound.

Following an initial phone conference, the subcommittee began its deliberations at BNL on September 6 and 7, with presentations from the four university facilities, the two major initiatives (RIA and Gamma-Ray Tracking - GRT) and the NSF low-energy facilities. This was followed by site-visits to the three national laboratory facilities: ANL on September 8-9, ORNL on September 10-11 and LBNL on September 28-29. During the national laboratory site-visits, the subcommittee also heard presentations summarizing the low-energy nuclear physics programs in Japan (at ANL), Europe (at ORNL) and Canada (at LBNL). A final meeting of the subcommittee was held in Oakland, CA on September 30. The agenda for the presentations at each of these meetings are listed in Appendix C.

Additional input to the subcommittee was solicited by DOE Program Manager Gene Henry from each of the smaller research groups funded by the DOE Low Energy Nuclear Physics Program. A number of emails sent by members of the community were also distributed to the subcommittee. A web site provided information to the community regarding the subcommittee's activities.

In the remainder of this report there is a presentation of the scientific opportunities for nuclear structure and nuclear astrophysics in Section 3. Section 4 discusses the existing capabilities within this subfield, including the DOE and NSF facilities as well as non-US facilities. The major new initiatives for the field are discussed in Section 5. Section 6 outlines the findings of the subcommittee.

# 3 Scientific Opportunities

The nucleus that lies at the heart of every atom is a unique many-body quantal system. This strongly interacting aggregation of fermions displays a remarkable diversity of phenomena and symmetries. The intricacies of its structure continue to surprise and fascinate nuclear scientists. Unexpected properties continue to be revealed by fresh experimental opportunities that arise from increasingly sensitive instrumentation along with new accelerator developments and new theoretical analyses. The present and near future will be very exciting periods in nuclear structure physics, and with RIA on the horizon the long term prospects for major discovery potential in this central field of nuclear science are spectacularly promising. The Holy Grail of developing a unified theory of the nucleus may soon be within our grasp.

In the last five years or so significant new discoveries and insights into the properties and behavior of the nucleus have been achieved. These advances have been through bold initiatives, both theoretical and experimental, in pushing our knowledge of nuclear systems to the limits. Such limits have included the creation and study of nuclei at the extremes of their existence in terms of atomic number and mass, angular momentum, excitation energy, deformation, temperature, and proton-neutron asymmetry. In concert with these experimental advances increased computing power and progress in computational techniques, along with new insights, have greatly enhanced theoretical progress in addressing the nuclear many-body problem.

Nuclei far from the valley of stability also participate in explosive nucleosynthesis in novae, x-ray bursts and supernovae via the rapid proton and neutron capture processes. One of the recent themes in low energy nuclear physics has been to produce these radioactive nuclei, study their properties, and in turn the origin of the elements in our universe. Much progress has been achieved in the study of light proton-rich nuclei with recently completed first generation Isotope-Separation On-line (ISOL) and fragmentation-based facilities to produce beams of radioactive isotopes. However, almost half of the heavy elements are believed to be produced by rapid neutron capture, and the proposed next generation RIA facility is essential to produce nuclei that participate in this process.

Recent results of neutrino fluxes observed by the SuperKamiokande and SNO detectors strongly support the conjecture that neutrinos have masses and flavor oscillations. New initiatives to study neutrino physics using atmospheric, solar, nuclear reactor and possibly supernovae neutrinos has emerged and are progressing rapidly. A quantitative understanding of neutrino production rates and spectra, via nuclear processes in stellar and explosive environments and in nuclear reactors is essential for this initiative.

The low energy nuclear physics program also aims to measure properties in nucleonic matter over the range of density and temperature accessible in collisions between heavy nuclei. There has been progress in this area; the compressibility of symmetric nuclear matter has been pinned down within rather small uncertainty, and evidence for critical phenomena at the liquid-gas phase transition of nucleonic matter has been obtained. These measurements place important constraints on theories used to model neutron stars, the most dense objects we observe, and violent type II supernovae explosions, which may provide the site for r-process nucleosynthesis and produce neutron stars.

Detailed studies of nucleon-nucleon and nucleon-deuteron scattering and of reactions between light nuclei are also conducted at low energy nuclear physics accelerators. These studies have helped build realistic models of forces between two and three nucleons which in turn are used for essentially exact calculations of few-body reactions and of all bound nuclear states having up to ten nucleons. Many of the light nuclei, $^{6}$He and $^{8}$He for example, have large neutron excess, and attempts to measure their properties in traps and by knockout reactions are in progress. Models of nuclear forces are also used to predict properties of hot and dense nucleon matter.

Nuclei also provide a laboratory to study fundamental interactions in nature, particularly the electroweak, and test the adequacy of the Standard Model. A great deal of progress has been made in testing the unitarity of the CKM matrix, a fundamental ingredient of the Standard model; the present data indicate a small violation by about two standard deviations. New experiments using radioactive nuclei produced by low energy nuclear physics facilities are under development to confirm this violation, as well as to probe the weak decays of nuclei for interaction terms beyond those admitted in the Standard Model.

Low energy nuclear physics thus has many important accomplishments and challenges. The next four subsections give an overview of the progress and opportunities in these subfields of nuclear science.

## 3.1 Nuclear Structure

Nuclei have collective degrees of freedom associated with their shape and their vibrations and rotations. Coupled to these are the single particle degrees of freedom associated with the quantum orbits occupied by the nucleons in the nucleus. These degrees of freedom produce a large variety of structures and excitation modes that can be classified using dynamical symmetries. Such classifications are also found to be useful in other branches of physics as well as other sciences such as chemistry. New structural modes are being found by in-depth observations of near-stable nuclei, as well as by experimenting with new nuclear species away from the valley of stability. Some of the recent discoveries include: a new form of quantum rotor called "magnetic rotation" or "shears bands" where excitations in essentially spherical nuclei produce highly regular band sequences reminiscent of the collective rotation of highly deformed nuclei. This regularity arises because the protons and neutrons both carry large angular momenta and the bands are produced by the variation of the angle between these momenta. In addition, a new class of deformed nuclei, with soft vibration modes exhibiting critical point behavior has been identified. Surprises have also appeared in our understanding of the shell model with the apparent disappearance of the magic number $N = 20$ neutron gap and the inversion of the shell ordering for very neutron-rich Mg and Na isotopes. Another example of new phenomena includes dipole oscillations of neutron halos against the core nucleons in neutron-rich nuclei.

Many diverse tools are used to study nuclear structure and excitation modes. Gamma-ray spectroscopy gives direct information on nuclear excited states produced in collisions and beta decays. Transfer reactions, as well as knock-out reactions in which nucleons are either added or removed from nuclei, are also useful probes of nuclear structure. Such reactions can be conducted in inverse kinematics on unstable nuclei produced by fragmentation.

**Gamma-Ray Spectroscopy** A central component in the highly successful US nuclear structure program utilizing gamma-ray spectroscopy, has been the Gammasphere. It is a National Facility funded by the DOE and designed and built by US national laboratories and universities. It is a spectrometer of unparalleled detection sensitivity for nuclear electromagnetic radiation. Its resolution, granularity, efficiency, and ability to be used in conjunction with a powerful suite of auxiliary detector systems have made it the ideal device for studying rare and exotic nuclear properties. Since its commissioning in 1995, its physics impact and productivity has been extraordinary.

In order to take full advantage of physics opportunities within the US community, Gammasphere has been successfully moved from LBNL (where it was constructed) to ANL and now back to LBNL. The physics addressed by Gammasphere has ranged over many issues from nuclear structure, to nuclear astrophysics, to tests of the Standard Model. At LBNL, for example, a major focus has been to investigate the behavior of nuclear systems with increasing excitation energy and spin. Many unexpected and surprising phenomena have been investigated and are beginning to be characterized, such as the shears bands mentioned earlier, new regions of nuclei displaying superdeformation, the still mysterious phenomena of isospectral structures (*i.e.* essentially identical emission spectra from neighboring nuclei), and new periodicities associated with a change of four units of angular momentum in superdeformed bands. In addition, the search is also on to discover if exotic hyperdeformed shapes really exist as predicted at the very limit of sustainable spins (70-80$\hbar$). At ANL, investigating the structure of nuclei far from stability was a central topic of research with beautiful results being obtained on nuclei at and beyond the proton drip line. Another major and surprising result has been the observation of very high spin states in $^{254}$No, far beyond those previously expected for such a heavy fissile nucleus. In addition, the discovery of superdeformed shapes in very light nuclei has opened up new opportunities to compare theoretical frameworks such as the shell model with effective interaction between valence nucleons and the simpler mean-field approach.

Smaller gamma-ray detector arrays also continue to play a crucial role. Experiments on transitional nuclei near N=90 have inspired new analytic predictions with regard to critical point symmetries and phase transitions in finite nuclei. Another exciting discovery has involved the observation of "chiral" partner bands brought about by the relative orientations of the angular momentum vectors of odd-proton and odd-neutron valence particles with that of a triaxial core. The whole question of stable triaxial nuclear shapes had been debated for decades and so this observation, along with the recent discovery of triaxial superdeformed shapes, has finally opened up the field of research involving triaxial nuclei where new symmetries and new collective modes of excitation are possible.

In the near future, Gammasphere will continue to act as a focus of the US nuclear structure community and therefore must be maintained in full working order and "upgraded" in a cost-effective manner when opportunities arise. However, in the longer term, there is no doubt that a $4\pi$ gamma-ray tracking array (see section 5.2) will provide enormous discovery potential beyond Gammasphere and will usher in a new era in nuclear structure studies both before and after RIA is built.

**Structure of Weakly Bound Nuclei** Understanding the physics of nuclei close to and at the drip-lines is of enormous consequence to our field. This is one of the central themes in the quest to build RIA. While RIA is absolutely necessary to obtain satisfactory answers to most of the major questions, some important work has already begun at NSCL and other national laboratories. Weak binding at the drip lines is certainly proving to have a profound influence on nuclear properties. For example, deep inelastic nucleon scattering reactions have shown that neutron halos in the so-called "Borromean" nuclei such as $^{11}$Li and $^{12}$Be have density distributions comparable to $^{208}$Pb in size. The addition of a single proton appears to "miraculously" allow the binding of up to 5 extra neutrons in fluorine compared to oxygen isotopes, and there are clear signs that the conventional magic numbers of nuclear structure may not be applicable away from stability. On the proton drip line, proton emission has been mapped out, mainly at ANL and ORNL, for all odd-A nuclei from In (Z=49) to Bi (Z=83). Many heavier proton emitters have also been observed. Such studies open up the interesting possibility of studying quantum tunneling without the "pre-formation" complexity of alpha decay. It has already been shown that deformation plays a critical role in the decay process of many nuclei. A new mode of nuclear decay, namely two-proton emission, has also been recently observed. All of these studies are still in their infancy and promise to provide us with many further surprises in the future.

A key breakthrough in studies of the structure of neutron-rich nuclei far from stability has recently been been made at ORNL. There, it has been convincingly demonstrated that important information on n-rich nuclei can be obtained via radioactive beams of only $10^5$-$10^6$ particles per second using Coulomb excitation, transfer and fusion-evaporation reactions along with gamma-ray spectroscopy.

In addition, ion and neutral atom trapping techniques have developed to the extent that isotope mass measurements are possible with beams of only few particles per second, and atomic spectra can be studied with beams of only $10^6$ particles per second.

**Summary** The field of nuclear structure covers a broad range of study. The examples above offer only a limited and incomplete sampling of the vast richness brought about by the complex interplay of single-particle and collective degrees of freedom in this unique quantal system. It is a field alive with new ideas and vital questions. The US nuclear structure community leads the world in many of these endeavors. It is critical that these exciting opportunities be fully exploited at existing stable and radioactive beam facilities, and that new instrumentation capabilities be vigorously pursued along with the nuclear physics community's commitment to build RIA.

## 3.2 Nuclear Astrophysics

Nuclear astrophysics is one of the forefront applications of nuclear physics in understanding our universe. It is concerned with the impact of the microscopic aspects of nuclear structure and reactions on the macroscopic phenomena we observe throughout the universe. Nuclear physics sets the conditions for the evolution of our universe within the first three minutes of the Big Bang. The characteristics of light nuclei such as the deuteron and triton determined the onset for the formation of the elements. The particle instability of mass 5 and mass 8 systems prevented the rapid formation of all the heavier elements and postponed their synthesis to the formation and evolution of stars.

Stellar evolution is directly correlated to its nuclear fuel. Hydrogen-induced reactions drive the energy generation in main-sequence and early red-giant stars, Helium-induced processes govern the evolution late in the red-giant phase and generate the neutron flux for the s-process, which is responsible for the production of about 50% of the heavy elements up to Pb. Fast convection and dredge-up processes spill the reaction products to the stellar atmosphere where they mix with the interstellar dust through solar wind driven mass losses and the formation of planetary nebulae. Heavy ion fusion and photon-induced fission processes characterize the final moments of stellar evolution prior to the collapse of the stellar core.

Neutrino and other weak interaction processes are closely associated with the physics of core collapse type II supernovae; they control the energy transport and originate the neutrino flux that revitalizes the stalled shock that drives the supernova explosion mechanism. Strong interaction processes, on the other hand, characterize the nucleosynthesis in the shock front through the outer layers of the pre-supernovae star. The neutron-rich gas in the neutrino driven wind near the core is thought to be the site of the r-process, which produces roughly half of the elements heavier than iron. All the nucleosynthesis processes in the shock front determine the abundance distribution in the ejecta and cause in particular the production of short-lived radioactive nuclei that power the characteristic light curve of supernova events.

The stellar remnants, left after the end of nuclear burning, are the white dwarfs, neutron stars, and possibly black holes. The white dwarfs and neutron stars contain most extraordinary forms of matter with densities up to few times $10^{15}$ g/cc. The mass-radius range, as well as the structure of neutron stars is primarily determined by nuclear forces, though there is a strong possibility of these stars having matter with strange hadrons or quark drops in their core. The matter in the core of type II supernovae explosions can also reach densities up to $10^{15}$ g/cc, and its equation of state is also governed by nuclear forces.

Stellar remnants that accrete mass from nearby companions can briefly flare back to life. Proton- and alpha- induced fusion processes far off stability drive the thermonuclear explosions on the surface of accreting white dwarf stars or neutron stars observed by astronomers as novae or X-ray-bursts. Depending on the accretion rate, type I supernovae or X-ray pulsars can be ignited. Other spectacular sites of rapid burning can be found in the accretion disks of black holes or in merging neutron stars.

**Astronomical Observational Opportunities** With construction of new ground-based telescopes and the launch of several satellite-based instruments the observational opportunities have multiplied over the last decade, spanning the entire range of the electromagnetic spectrum. Four major observational signatures for nuclear processes within stellar sites have emerged:

- The luminosities of stars and the light-curves of stellar explosions, which are directly correlated to the nuclear (and sometimes also) gravitational energy release.

• The observed abundance distribution in stellar spectra, in the ejected material of stellar winds (planetary nebulae) and stellar explosions (novae, supernovae), and in meteoritic inclusions, which are condensates of ejected matter in the interstellar space.

• The stellar neutrino flux, which was thought to give a unique, unequivocal signal of the nuclear reactions in the core of our sun or distant stellar explosions.

• Nuclear gamma-rays emitted by astrophysical objects, which give direct information on the produced radionuclides.

Light-curve analysis is of particular interest for stellar explosions, since it offers information about the time-scale of nuclear energy release and the associated rapid nuclear processes. The analysis of elemental and isotopic abundances is a powerful tool if we have site-related observations where we can directly correlate the observed abundance distribution with the predicted nuclear and hydrodynamic nucleosynthesis processes. Neutrino observations originally were thought to give insight into the nuclear physics aspects only. However the "solar neutrino problem" indicated that the signature itself may be changed by neutrino oscillations processes which now seem to have been confirmed by Superkamiokande and SNO observations. These and previous observations have stimulated a new side branch of nuclear astrophysics, neutrino physics using the sun (and hopefully future near-by supernovae) as neutrino generators allowing us to investigate the characteristics and nature of the neutrinos and their interactions with matter. This, in turn, requires detailed knowledge of the originating nuclear processes.

**Experimental Nuclear Astrophysics Opportunities** The interpretation and the deeper understanding of the nature of these stellar events and their observed signatures, is still in its early stages. The theoretical models are rather crude and are often based on global assumptions. Better and more detailed microscopic input information is clearly needed to compare the observations with model predictions and to come to a better understanding of the nature of these events. Experimental nuclear astrophysics offers the unique opportunity to simulate stellar processes and the associated nucleosynthesis in the laboratory. The experimental simulation of stellar conditions in the laboratory is the crucial link for interpreting the wealth of observational data through complex computer simulations of stellar evolution and stellar explosions. Two major goals have crystallized over the last decade. The first centers on the understanding of nuclear processes far off stability in the rapid proton (rp-) and neutron (r-) capture process, which characterize nucleosynthesis in novae, X-ray bursts, and supernovae. The second goal focuses on understanding nuclear burning through the different phases of stellar evolution, determining the lifespan of the stars and the ignition conditions of stellar explosions. They also determine the elemental and isotopic abundances observed in stellar atmospheres and in the meteoritic inclusions.

Questions involving nuclear processes during stellar explosions can be addressed with the construction of radioactive beam facilities which offer the opportunity to study the associated nuclear capture and decay processes at the limits of stability. The construction and operation of the first generation radioactive beam facilities have already provided significant results for the understanding of nucleosynthesis processes during the Big Bang and during nova explosions. The use of ISOL and fragmentation techniques extended the measurements closer to the drip lines and permitted the first measurements of decay processes along the rp- and the r-process path. The construction of RIA as the next generation radioactive beam facility will provide unique opportunities for the nuclear astrophysics community to extend the measurements to more complex nuclear processes along the rp- and r-process paths at the extreme conditions of X-ray bursts and supernovae.

The development of a new generation of radioactive beam facilities like RIA is necessary to simulate the conditions for rapid nuclear reaction processes which occur within the split-second time-scale of a stellar explosion. Quite opposite conditions are necessary for the study of nuclear reactions during the long-lasting quiescent periods of stellar evolution. High intensity, low energy accelerators for stable beams are required to simulate the nuclear processes that last for thousands and millions of years and define the life of a star. More than thirty years of intense experimental study lead to the understanding of the major concepts for nuclear burning during stellar evolution. The rapid development of detector, electronic, and accelerator technology over the last decade offers new opportunities to extend these measurements to smaller cross sections and to new lower limits, far beyond the available data. Presently available low energy accelerator facilities offer unique opportunities to perform these studies for extensive periods of time. In the future underground accelerator facilities will offer a unique low-background environment for performing a new generation of low cross section measurements near solar temperature conditions.

## 3.3 Reactions: Nuclei at Extremes of Temperature, Density and Isospin

During the past decade nuclear reaction studies with conventional beams have yielded major new insights into the behavior of finite nuclei subjected to extreme conditions of temperature and density. In particular these investigations have produced significant advances in our understanding of the dynamic and statistical properties of strongly interacting mesoscopic systems. The range of phenomena under investigation spans the temperature domain extending from relatively cold nuclear systems to the nuclear vaporization limit, as well as the density profile from dilute to compressed nuclear matter.

**The Nuclear Equation of State** Studies of nuclear giant resonances have considerably improved the value of the nuclear incompressibility constant for nuclei at low temperatures undergoing small amplitude density oscillations about their normal density. For systems heated to energies approaching the total binding energy, convincing evidence for a nuclear liquid-gas phase transition and critical behavior in hot, dilute nuclei has recently been reported. Spurred by theoretical investigations, related experimental studies have begun to search for the effect of isospin fractionation on neutron-proton phase separation, analogous to the behavior of classical binary systems. While preliminary evidence for such a process has been presented on the basis of reactions with stable beams, studies with much greater isospin variation are required to verify the result. Still higher energy collisions have created nuclei compressed to densities over twice that of normal nuclei. Taken as a whole the temperature-density profile afforded by these observations should help establish important new constraints on the nuclear equation of state, and in turn the behavior of neutron stars and type II Supernovae explosions.

The challenge for future equation of state investigations is to focus on the neutron-proton degree of freedom. Since the energy density of the nucleus depends quadratically on isospin, knowledge of the influence of this parameter is critical to a full understanding of the nuclear liquid-gas phase transition.

**The Link between Reactions and Structure** In parallel with efforts to understand the nuclear equation of state, new initiatives have begun to explore the interface between nuclear structure and the continuum regime. While the deformation landscape at the limits of isospin will be explored using gamma-ray spectroscopy, nuclear reaction studies will focus on the influence of isospin on nuclear level densities. The evolution of the nuclear level density with excitation energy has revealed the loss of enhancement due to coupling to surface excitations. Theoretical work has provided a better definition of the influence of the continuum on nuclear level density. This issue becomes increasingly important for highly stretched nuclei that link with the superdeformation region and for nuclei that approach the neutron-drip line, since the physics at the bound-continuum interface impacts in a major way on our ability to model r-process nucleosynthesis. In this effort a close collaboration between the reaction and structure fields will be essential.

Highly stretched nuclear shapes are also being investigated via damped collisions and fission, serving as an important link to the superdeformation region at low energies. In addition, systematic fission studies have quantified the shell and parity corrections to heavy element fission barriers and fusion barrier measurements are underway in order to determine the most effective pathway for the synthesis of new heavy elements. The quest to observe the fabled island of super-heavy elements is beginning to appear closer on the horizon.

Finally, at the most fundamental level the spin dependence of reactions involving few-body systems continue to refine our knowledge of the nucleon-nucleon interaction and construct realistic models of the nuclear force.

**Isospin: the Focus for the Future** Isospin-related studies will constitute the major thrust of the nuclear reactions community in the future. RIA, of course, is the vital element in the full exploitation of the isospin variable for exploring the nuclear equation of state and the structure-continuum interface, as well as the search for super-heavy elements. Significant progress in these areas can be made over the next decade at the fast fragmentation and stable beam facilities that are currently in existence or coming on line. However, important needs must be met to accomplish these goals.

For the effective interpretation of any experimental program, strong theoretical support is essential. A major challenge exists in coupling transport theory and decay dynamics in a self-consistent way. Simulations are needed to translate data from finite nuclear systems into meaningful parameters of the nuclear equation of state. However, at present the U.S. effort in this area is small.

Technical advances, which have been key to progress in the field over the past decade, must also continue to evolve to meet the demands of the higher level of sophistication required for studies with radioactive beams. First generation $4\pi$ charged particle arrays are now being replaced by highly granular, large dynamic range particle-identification telescopes based on silicon-strip technology. These devices must provide the energy, angular and isotopic resolution necessary for inverse kinematics experiments with fast fragmentation beams, ranging from simple stripping and pickup reactions to high multiplicity multifragmentation reactions. Development of these detector arrays places new demands on signal-processing electronics and data-acquisition systems. Versatile chipset electronics are being developed to meet this need, along with the computer codes needed by the community to use these devices efficiently. Charged particle arrays are being coupled with detectors for simultaneous measurement of gamma rays or neutrons. These advances will enhance our ability to acquire data at a new level of significance and at the same time efficiently utilize the limited beam time and low intensities that will be commonplace at radioactive beam facilities.

Finally, it must be kept in mind that the advances in nuclear reaction mechanism studies provide the pathways for exploring neighboring areas of low energy nuclear physics. A few examples include: selection of the proper fusion entrance channel for structure or heavy element searches, implementation of charged-particle arrays for structure or heavy-element searches, use of pickup and stripping reactions for nuclear astrophysics, fission and fragmentation data for radioactive beam production via both ISOL and fast fragmentation techniques.

**Summary** The nuclear reactions field has experienced major advances over the past decade in understanding the physics of mesoscopic systems as a function of temperature and density, as well as in developing powerful detector systems for these studies. For future progress in this field, research must focus on the extremes of isospin in order to explore the potentially exciting new physics that will emerge with radioactive beams.

## 3.4 Fundamental Interactions

Novel phenomena in low-energy nuclear physics continue to offer unique opportunities to probe the fundamental electro-weak interactions. Such measurements provide critical information on key elements of the Standard Model, as well as searching for new physics beyond this Model. Our subcommittee was charged with reviewing those components of this sub-field that take advantage of the facilities funded by the low-energy nuclear physics programs of NSF and DOE. Included within this charge are the production of radioactive nuclei for both precision beta-decay studies and atomic parity violation measurements using radioactive atoms.

**The Unitarity of the CKM Matrix** The eigenstates of the weak interaction between quarks are not the same as those of quarks in hadrons. Thus there is a mixing among quarks following a weak interaction. This mixing is governed by the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The most precisely known component of this matrix, $V_{ud}$, describes the weak coupling between the up and down quarks. This component is extracted from measurements of the $ft$ values in $0^+ - 0^+$ nuclear beta-decay and thus requires precision measurements of beta-decay lifetimes, branching ratios and nuclear masses. Measurements on a large number of different nuclei are required to minimize systematic uncertainties associated with various nuclear corrections that allow the conversion from the measured $ft$ values to $V_{ud}$. Production of these nuclei (some of which are fairly short-lived) requires low-energy accelerators with related equipment.

Because of the precision presently attainable in measurements of $V_{ud}$, sensitive tests of the unitarity of the CKM matrix are possible. Within the Standard Electro-Weak Model with 6 quark flavors, the CKM matrix should be unitary and any deviations are indications of new physics beyond the Standard Model. Present data suggest approximately a $2-\sigma$ deviation from unitarity and future measurements of $V_{ud}$ (which is by far the dominant component in the unitarity sum) will attempt to identify if this is simply a statistical fluctuation or evidence for a breakdown of the Standard Model.

**Search for New Components of the Electroweak Interaction** Precision beta-decay measurements can also be used to directly search for new physics outside of the Standard Model. Careful measurements of correlations between the emitted electrons or positrons with the recoiling nucleus or with beta-delayed alpha particles or gamma-rays allows the structure of the Electro-Weak interactions to be probed. Within the Standard Model the interaction is purely left-handed with a (Vector − Axial-Vector) current structure. Precision correlation measurements are sensitive to possible new components of the interaction that may allow right-handed currents and Scalar and Tensor couplings. Such new components to the Electro-Weak interaction can arise from the effects of new very massive particles ($M > 1$ TeV) that have yet to be observed at high-energy accelerators.

**Atomic Parity Violation** Atomic Parity Violation measurements with radioactive species can also be performed at low-energy facilities. Such measurements provide precision information on the weak charge of the nucleus, from which the elementary quark Electro-Weak couplings can be determined. In addition, by separately measuring the parity-violating effects in different hyperfine states, information on the nuclear anapole moment can be determined. Recent measurements with stable Cs atoms have given first evidence for this subtle Electro-Weak phenomenon. Significantly enhanced sensitivity is possible by extending the weak charge and anapole moment measurements to heavy atoms. In particular, the heaviest alkali atom Fr offers a number of promising unstable isotopes for improving these measurements.

**Summary** In order to take advantage of these exciting opportunities at existing low-energy facilities and in preparation for dramatic increases in the production of radioactive species possible with RIA, new technologies are under development. These technologies include novel schemes for ion traps allowing precise mass measurements, high precision gamma-ray spectroscopy for measurements of sub-percent beta-decay branching ratios, and radioactive atom traps for beta-decay correlation studies and for investigating atomic parity violation. These important technological developments have occurred because of the availability of a number of low-energy facilities that enable this science to be pursued.

# 4 Experimental Capabilities

Low energy nuclear physics research is mainly carried out at university- and national laboratory-based accelerator facilities. While each of the facilities has notable strengths, the different research programs at the various accelerators complement one another in many important ways. All together, they are part of a coherent national effort in low energy nuclear science. While the long-term progress of the field requires the design and development of the next generation radioactive beam facility RIA, the wide range of scientific questions and problems requires the continued operation of the world-class program in low energy nuclear physics at the present accelerator facilities. In addition to being the backbone of the current programs, the existing accelerators will play a crucial role in carrying out critical R&D relevant to RIA as well as in ensuring the existence of a healthy community of researchers and students when RIA comes on-line.

## 4.1 DOE funded Facilities

This subcommittee was asked to address the three national laboratory facilities and the DOE university laboratories in light of their capability to carry out the research programs outlined in the previous section. These facilities provide a broad spectrum of complementary research capabilities from high intensity low mass beams to the moderate intensity beams of the heaviest stable elements. In addition, a range of radioactive beams at different energies is now available. This spectrum of beam capabilities along with a rich array of specialized spectrometers and detectors form the basis for the DOE experimental low energy nuclear physics program. As an example of why a broad range of facilities is necessary to address the physics questions, let us consider nuclear astrophysics questions. There is a considerable range of stellar burning conditions - from slow quiescent burning of main sequence stars to rapid nuclear processing in stellar explosions. For the slow burning in stars: low energy high intensity accelerators are the ideal tool for studying charged particle processes; a wide variety of laboratory neutron sources is necessary for the simulation of s-process nucleosynthesis; and real and virtual photon beam experiments are at the verge of developing into a major tool for the study of charged particle and $\gamma$-induced processes. Finally, radioactive beam experiments using ISOL and fragmentation techniques have opened new and unique opportunities to study nuclear astrophysics questions at the limits of particle stability.

Major investments have been made both by the DOE supported national user facilities as well as University facilities to develop and provide a large range of experimental tools for addressing a broad spectrum of questions in low energy nuclear physics and astrophysics. In the following, we shall describe each of the major facilities in some detail, and point out their unique strengths and capabilities for supporting an active and developing research program.

### 4.1.1 ANL

The Argonne Tandem Linear Accelerator System (ATLAS) at Argonne National Laboratory has a broad-based program in low energy nuclear science. The strength of the program rests on the effective integration of a strong local scientific staff, an extensive group of active users, and an innovative accelerator physics group.

The first superconducting heavy ion linac was developed at Argonne and the ANL accelerator physics group has continued to make innovations in the field. Last year the group demonstrated the simultaneous acceleration of uranium ions with eight charge states to the same final energy through a portion of ATLAS. This has implications for the high-intensity acceleration of heavy ions that is limited by ion-source intensities, such as for RIA.

The independently phased superconducting resonator technology developed at Argonne for ATLAS is the basis for both the high power heavy-ion driver and the post accelerator for ISOL-type beams of exotic isotopes at RIA. Continuous development of this and related accelerator technologies and the associated instrumentation for fundamental investigations in nuclear science is essential to the national program leading to greatly expanded capabilities of the future RIA project. Scientists and engineers from several divisions at Argonne are actively pursuing the development of the technologies that form the underpinnings of RIA.

The present accelerator system consists of a LINAC of independently phased superconducting resonators that is usually injected with an ECR source and the positive ion injector. The system is very flexible and has much redundancy, so that continuation of an experiment is usually possible with failure of some components. Figure 1 shows the stable beams that have been run at ATLAS during the last 5 years.

The scientific program at the ATLAS facility is many-faceted. One of the most exciting capabilities was the coupling of Gammasphere to the Fragment Mass Analyzer (FMA) to study nuclei far from stability with excellent channel selection. For example, the first measurement of the structure of a transfermium nucleus (Z=102) confirms that the shell-correction energy responsible for the stability of such nuclei is derived partly from deformation and shows that these heavy, fissile nuclei are more robust against rotation than had been thought. Another recent important spectroscopic result is that the first superdeformed band ever found, in $^{152}$Dy, has finally been linked to the yrast line through a high-energy $\gamma$-ray observed with Gammasphere. The excitation energy and the quantum numbers of the superdeformed states have been established. This technique was pioneered by the ANL group on nuclei near A=190.

ANL has initiated a nuclear astrophysics program that is centered around the development of long-lived radioactive beams such as $^{18}$F, $^{44}$Ti, and $^{56}$Ni to study critical reaction and decay processes for our understanding of nova and supernova nucleosynthesis. This approach leads not only to astrophysically relevant results but also helped to develop new experimental techniques for reaction studies with extremely limited beam intensity. These techniques will be crucial for future experiments of similar kind at the proposed RIA facility. Complementary to these studies with off-site produced long-lived radio-isotopes, on-line produced short-lived $^{17}$F beams were developed for a pioneering study of the reaction $^{17}$F(p,$\alpha$)$^{14}$O to gain knowledge about break-out processes from the hot CNO cycles. These experiments were performed in collaboration with ORNL and others and provided important data for future studies with the intense HRIBF $^{17}$F beams. In another investigation, cross sections were measured for the $^{44}$Ti($\alpha$, p)$^{47}$V reaction, which may significantly affect the yield of $^{44}$Ti in supernovae. This is a result clearly important for the interpretation of observations

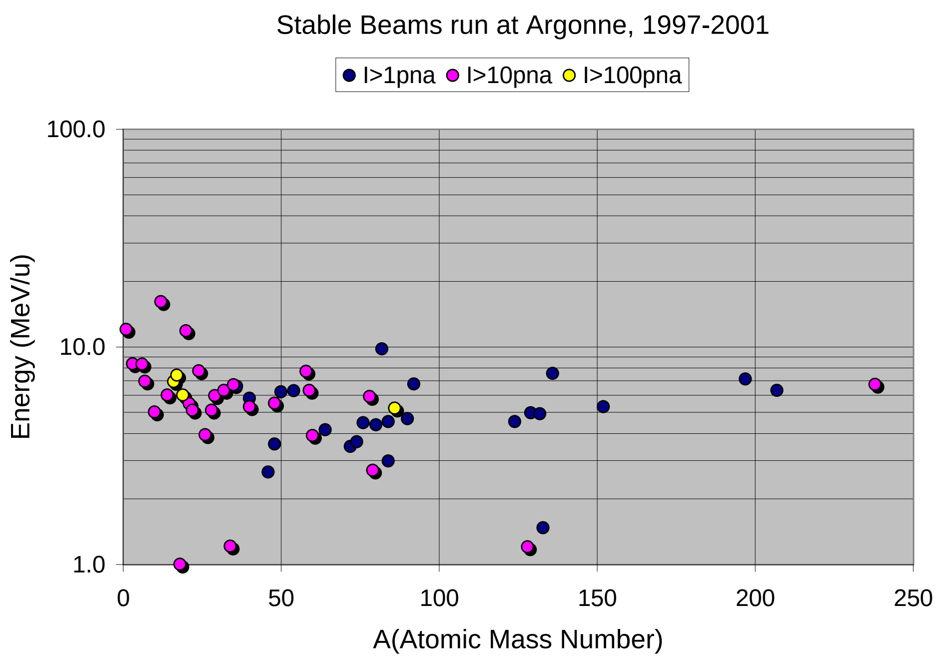


Figure 1: Stable beams used in experiments at Argonne National Laboratory during 1997-2001. These beams may not be the most energetic or the most intense that the facility is capable of producing, but represent what has been requested by the experimenters.

of soon to be launched $\gamma$-ray observatories like INTEGRAL.

Another significant experimental effort at ANL is associated with the Fragment Mass Analyzer (FMA). The FMA was instrumental in conjunction with Gammasphere for the successful application of recoil tagging techniques for nuclear spectroscopy up to very heavy nuclei. The FMA has also been crucial for a pioneering study of proton emitters to map the drip-line. These experiments successfully employed a broad range of Si-strip detector arrays. Recently, the first observation of proton radioactive decay to an excited state in the daughter was reported for $^{131}$Eu. The ANL group has also made the first direct confirmation of deformation in a proton-emitter through the observation of rotational bands in $^{141}$Ho with Gammasphere and the FMA. The FMA was also used as a major tool for nuclear astrophysics studies near the proton drip-line.

The flexibility of the ATLAS accelerator facility has been crucial in developing experimental methods for trace element detection for application in dating and environmental studies. This work continues with the development of a potential method to study $^{39}$Ar, with a half-life of 269 years, that is ideal for studying ocean circulation patterns. Another very exciting capability was recently developed at Argonne to detect single atoms of rare gases with laser trapping techniques [Atom Trap Trace Analysis (ATTA)].

The Canadian Penning Trap is currently installed at ANL, and has the capability of making precision mass measurements of nuclei far from stability. Products from heavy-ion reactions are collected with a large aperture quadrupole and separated from the beam with a Wien filter and a gas-filled Enge split-pole spectrometer. These products are then slowed in a He gas cell, and stopped as $1^+$ ions. The ions are then transported by DC and RF electric fields to the nozzle of the gas cell, where they begin the path to the Penning Trap. The gas cell technology developed for this experiment is a prototype for the larger gas cell at the heart of the RIA project.

A unique asset of the ANL program is their target manufacturing capabilities. This expertise at ANL allows highly specialized targets to be prepared for various beam experiments at many laboratories. It is important that these capabilities be maintained given the continuing demands for such targets.

In summary, the Argonne ATLAS program is very active and productive, and broadly based scientifically. It is closely connected with the future direction of the field towards RIA. The program, like most of the components of the Low Energy Nuclear Physics program, is constrained financially from developing at an optimal pace, and there are clear strains from carrying out an active research program and an active R&D program for RIA that could be relieved with increased funding for personnel.

### 4.1.2 LBNL

The 88-Inch Cyclotron at Lawrence Berkeley National Laboratory supports a wide range of low energy nuclear science for a large international community of users. The central component is a sector-focused, variable-energy cyclotron that can be fed by either of two ECR ion sources. This versatile combination produces heavy-ion beams of elements throughout the periodic table. For helium to oxygen, beam energies are up to 32 MeV/nucleon; for heavier ions the maximum energy per nucleon decreases with

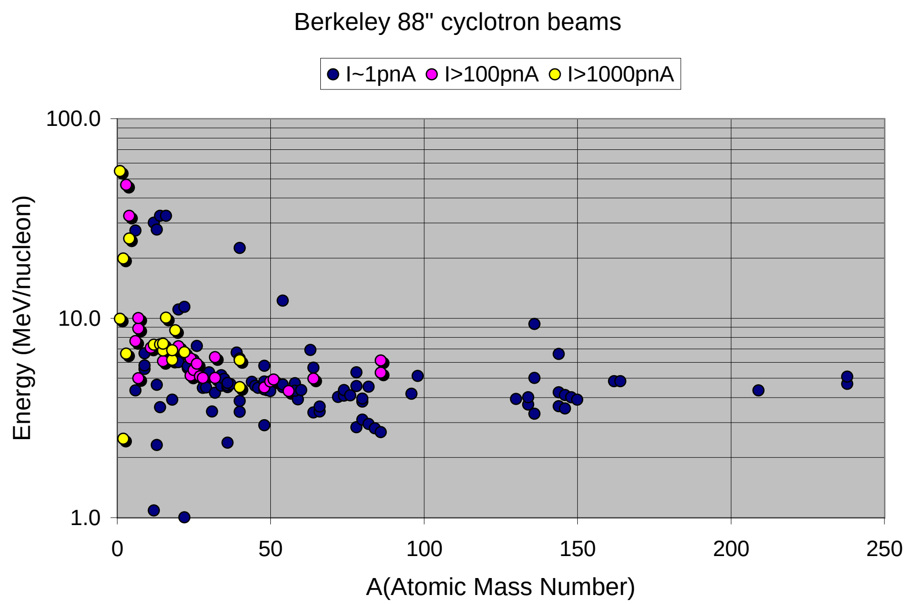


Figure 2: The stable beams that have been run at the 88" cyclotron in the last few years are shown.

increasing mass reaching 5 MeV/u at bismuth. Light ions are available at intensities of 20 p$\mu$A. Figure 2 shows graphically the stable beams that have been run at LBNL in the last few years.

The ECR group at LNBL has a long history of outstanding new source developments that has been incorporated at other labs, including ANL, MSU and Jyväskylä. Their new source, VENUS, continues in this tradition, with a superconducting magnet and operation at 18 and 28 GHz. Because of the high intensities of high charge state ions, even the ion beam transport system required new developments. When completed, VENUS will significantly extend the capability of the cyclotron to higher mass and higher intensities. An ECR source such as VENUS may also be the source of choice for the high intensity heavy ion driver linac of RIA.

Gamma-ray spectroscopy has always been and continues to be a primary activity at LBNL. Gammasphere, currently the world's most powerful instrument for detecting gamma rays, was developed by the national gamma-ray community led by LBNL and currently resides at the 88-Inch Cyclotron. The possibility of tracking individual gamma rays in a detector has been studied extensively at LBNL and other places, and a new device, GRETA has been proposed. GRETA would significantly increase the sensitivity for gamma ray spectroscopy when many gamma rays are emitted, and the position sensitivity could greatly improve Doppler corrections.

The gamma ray research program at LBNL has very effectively utilized Gammasphere and its auxiliary detectors for studying the properties of nuclei at large angular momentum. The phenomenon of "shears bands", where the orientation of odd particles changes with increasing angular momentum has been extensively studied and characterized in both the Pb and Cd regions by the LBNL group. Another recent achievement of the LBNL group has been an extensive study of np pairing in nuclei. The LBNL group has continued to make searches for superdeformation and has recently observed superdeformed bands in $^{36}$Ar and in $^{108}$Cd. In $^{36}$Ar, a large number of energies, spins, parities, and B(E2)'s have been measured that allows a detailed comparison with theory.

The heavy element chemistry group, as part of an international collaboration, has recently been successful in determining the chemical properties of element 106, Seaborgium, and element 107, Bohrium. In both cases the elements continued to have similar chemical behavior appropriate to their column in the periodic table. The Bohrium study, done with 6 atoms in 30 days, showed that the heat of absorption of the $O_3Cl$ becomes more negative as Z increases. Experiments with element 108, Hassium, are underway by the collaboration.

At present, the unique combination of high intensity stable beams such as $^{51}$V, $^{64}$Ni, and $^{86}$Kr and the BGS high efficiency separator are essential for the production and detection of new superheavy elements. The BGS has recently undergone extensive testing of the new system and has successfully confirmed the discovery that had been made previously at GSI of element $^{271}110$. The reaction used was $^{208}Pb(^{64}Ni, 1n)^{271}110$. There is also significant promise for heavy element spectroscopy in the intermediate and longer term by combining the BGS with the initial three or four modules of the proposed Gamma-Ray Tracking detector.

An exciting research program that relies on the high intensity light ion beams is the ambitious effort to make a precision measurement of the $\beta - \nu$ correlation in the decay of laser-trapped $^{21}Na$. The large beam intensity has allowed the group to work with trapped atom samples on the order of $10^6$ atoms. This program is on the verge of publication of its latest result.

The nuclear astrophysics program at Lawrence Berkeley Laboratory concentrates on the question of weak interaction and neutrino properties. This program uses the 88-Inch Cyclotron only to a limited extent, e.g. for the production of radioisotopes like $^{44}$Ti. A significant initiative has been undertaken in the construction of the BEARS facility, which provides a limited range of relatively high intensity radioactive beams in the CNO range. The facility is based on the use of a production cyclotron for generating the radioactive isotopes that are fed, by a rapid He-jet transport system, into the ECR source of the 88-Inch Cyclotron, which serves as the post-accelerator facility. This approach utilized the laboratory's unique experience in fast transport techniques for radioactive species and its world-wide leading role in ECR source development. First measurements with $^{11}$C have been successfully performed, in close collaboration with HRIBF at ORNL, and represent an example of utilizing each laboratory's complementary capabilities and utilities. The development of an intense $^{14}$O beam is a milestone development for alpha capture measurements with radioactive oxygen beams in inverse kinematics. BEARS appears as a unique alternative to main-stream radioactive beam laboratories and can be utilized for long-term reaction studies with radio-isotopes in the minute to second lifetime range. In a separate development, a world-record for $^{14}O$ production was achieved using the 88-Inch Cyclotron as a driver and the IRIS ion source to produce a low energy beam for weak interaction studies.

In summary, the 88-Inch Cyclotron supports a strong research program, with great strength in gamma ray spectroscopy and gamma-ray detector development. The intense beams of light ions have made possible a strong program for measuring weak interaction parameters with laser-trapped radioactive atoms. LBNL has a unique capability and a long history of heavy element synthesis and chemical study. Finally, the work of the accelerator group in radioactive beam development, and the development of new sources by the world-class ECR group continue to keep the cyclotron operating as a productive machine.

### 4.1.3 ORNL

The Holifield Radioactive Ion Beam Facility (HRIBF) is a first-generation Isotope Separation On-Line (ISOL) radioactive ion beam (RIB) facility developed, in a cost-effective way, to make use of existing accelerators at ORNL. The 25 MV tandem accelerator is used for both stable and unstable beams. Typical beam energies and currents available for stable beams are shown in Figure 3.

Radioactive species are produced by intense light-ion beams from the Oak Ridge Isochronous Cyclotron (ORIC) and post-accelerated by the 25MV tandem electrostatic accelerator. Linking production and post-acceleration is the RIB Injector system, consisting of a high-voltage platform on which the production target ion source and beam preparation and purification hardware reside. The suite of radioactive beams available for research has expanded rapidly in the last year with the development of fission product beams. These beams have been greatly facilitated by development at Oak Ridge of a very porous graphite matrix that allows rapid diffusion of the reaction products out of a uranium carbide target formed from this porous material.

The unique radioactive beams available at ORNL can be put into perspective by comparison with the radioactive beams that are currently available at all facilities in the world. Figure 4 plots the beams that are available world-wide.

A great strength of the facility is the suite of state-of-the-art experimental equipment, carefully optimized for nuclear structure research with RIBs, including the RMS recoil separator and the CLARION gamma-ray array. One of the most surprising and exciting recent studies made possible by these facilities and the unique medium mass radioactive beams has been the Coulomb excitation of $^{126,128}Sn$ and $^{132,134,136}Te$ nuclei near the N=82 magic number. The B(E2) values show the expected minimum at N=82 for Xe, Ba and Ce, but the most neutron-excess beam measured, with N=84, $^{136}Te$, shows an even lower B(E2) than for the N=82 nucleus. This result indicates that pairing may change for large neutron excesses.

The Daresbury Recoil Separator (DRS), equipped with an array of silicon strip detectors, an ion chamber, and a windowless hydrogen gas target designed for radiative capture, scattering, and transfer reactions is now dedicated to the astrophysics

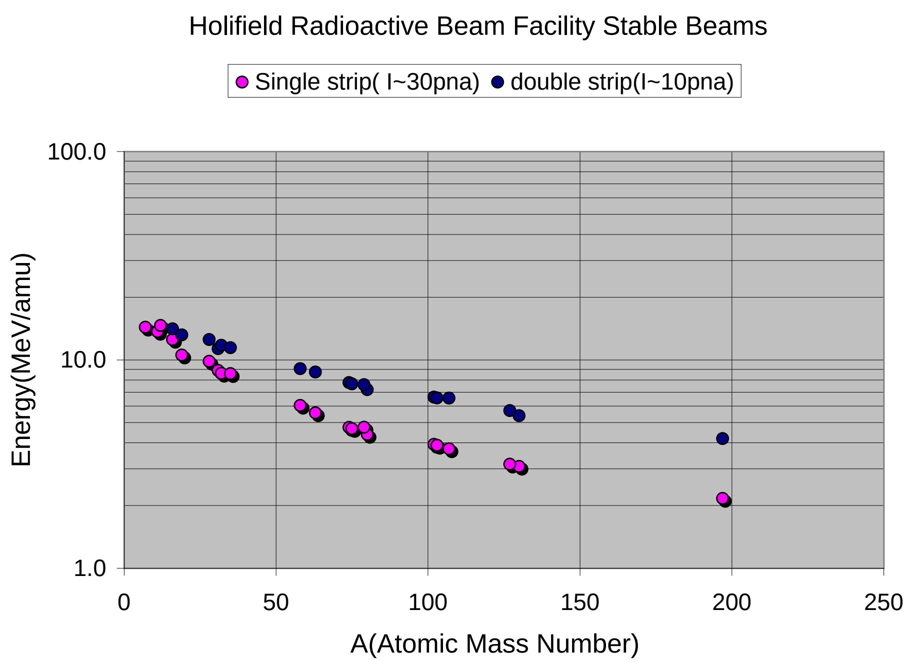


Figure 3: Holifield Radioactive Ion Beam Facility stable beams. As the focus of HRIBF has been on radioactive beams, what is shown are typical stable beams that can be run routinely.

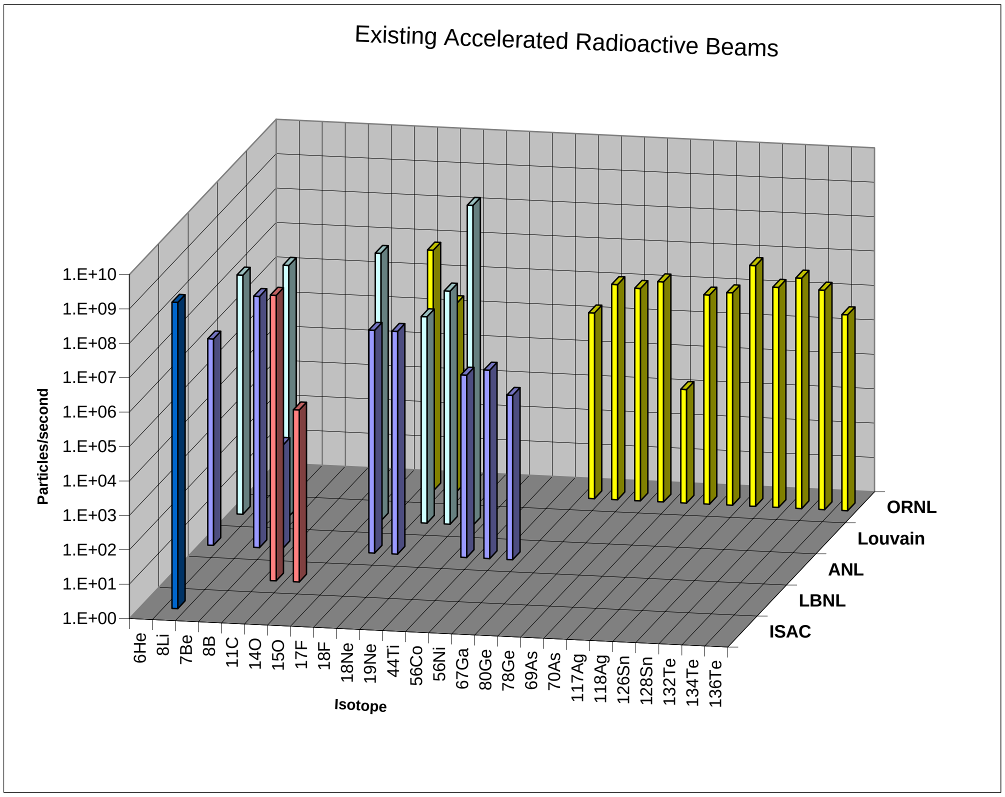


Figure 4: Intensities of existing accelerated radioactive beams (as of 9/2001) are plotted for different beams and facilities. Only accelerated beams with $E > 1MeV/A$ are plotted.

program. The astrophysics group at HRIBF has focused on the development of $^{17,18}$F beams to study the hot CNO nucleosynthesis in novae. The development of on-line production of these beams presented considerable technological challenges but has been successful. The measurements of $^{17,18}$F(p,p) have been completed. The study of $^{18}$F(p,$\alpha$) complemented and improved previous results obtained at Louvain-la-Neuve and Argonne. These studies provide important information on the rates of proton capture reactions on fluorine isotopes in hot CNO cycles that drive novae explosions. Part of this work was a PhD. thesis (Yale University) that was awarded the 2000 APS thesis award in nuclear physics. The measurement of $^{17}$F(p,$\alpha$)$^{14}$O provides important information for the strength of the inverse $^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}$ reaction, which is one of the key processes for the break-out flow powering X-ray bursts and X-ray pulsars. Such measurements are needed to reduce the large uncertainties in the prediction of the synthesis of rp-process nuclides. The nuclear astrophysics group profits from close collaboration with the astrophysics theory group at ORNL, and this helps to identify new goals and future experimental directions at HRIBF.

In the last three years five new proton emitters were identified by the HRIBF group, including the 3.5$\mu$s emitter in $^{145}$Tm, the shortest yet measured. This work again used the flexible Clarion $\gamma$-ray array and the RMS spectrometer. In addition, a digital signal processing technique allowed separation of proton decay signals from the implantation signal separated by less than a $\mu$s. Proton emission has been used as a tool for studying proton and neutron orbitals in nuclei beyond the proton drip line. Detailed studies of proton emitters along the N=Z line at $^{100}Sn$ are of great help in understanding the termination of the rp-Process. Besides the study of proton emitters, the life-time measurements of nuclei along the N=Z line (e.g. $^{80}$Zr, $^{84}$Mo) provide important information on the time-scale of the rp-process and the identification of the rp-process endpoint. The use of Ge-clover detectors at the focal plane of the RMS was crucial for identifying new isomeric states in Zr and Y isotopes near the proton drip line. The successful measurement of the $\beta$-decay component of these states again adds important information for the analysis of the rp-process reaction flow and end-point during the cooling phase of X-ray bursts.

The radioactive beam capability of the HRIBF provides a unique opportunity for the US low energy nuclear physics community to develop experimental expertise and techniques with radioactive beams for RIA. While light ion radioactive beams are available at several laboratories worldwide, the experimental equipment available at HRIBF for studying the properties of, and reactions with, these ions is clearly unique and identifies HRIBF as a prime site for low energy radioactive beam studies for the next several years. The availability of medium-mass neutron rich accelerated beams itself is unique world-wide. The HRIBF has made significant contributions to the technology of RIB production, including new-concept ion sources optimized for RIBs, and novel, highly effective production-target formats. Many of the existing and planned experimental tools and equipment have direct application for future research at RIA. Similarly, the HRIBF can continue to play a key role in the training of manpower and development of ISOL radioactive beam research while RIA is being developed and brought on-line. The performance and efficiency of this facility can be dramatically enhanced with a modest investment of new funds in the interim period.

In summary, the HRIBF program at ORNL is very active and productive. Scientifically it clearly focuses on the study of nuclei far from stability at the intersection of nuclear structure and nuclear astrophysics. This identifies HRIBF as a prime site in the US for pre-RIA radioactive beam measurements.

### 4.1.4 Texas A&M

The Cyclotron Institute of Texas A&M operates a K500 superconducting cyclotron, with two high performance ECR sources. The Cyclotron Institute is a recognized leader in research on the incompressibility of the nucleus through studies of the Giant Monopole and Isoscalar Giant Dipole Resonances in medium and heavy nuclei. It also carries out a program of investigations of the properties of collisionally heated nuclei and the statistical mechanics of strongly interacting, finite quantum systems up to the limits of thermal and rotational stability. Fundamental symmetries work is mainly concentrated on precision measurements of $\beta$-decay lifetimes and branching ratios for superallowed $0^+ \to 0^+$ transitions for tests of the unitarity of the CKM matrix.

Over the last decade a strong astrophysics initiative has developed at Texas A&M, partly motivated and driven by the in-house theory group, and partly by the technical advantages the facility has to offer. This effort concentrates mainly on the experimental determination of single particle structure signatures, the Asymptotic Normalization Coefficient(ANC), which is proposed as a model-independent determination of non-resonant low energy direct capture contributions not accessible in direct measurement. This method would be particularly useful for extrapolating high energy data, taken with both stable and radioactive beams, to stellar energies. A rich experimental program has developed to test and verify the method, focusing on reactions in stellar hydrogen burning like $^7$Be(p,$\gamma$), and $^{16}$O(p,$\gamma$) to compare the ANC predictions with available data from low energy capture measurements. Presently first steps from the theoretical side have been taken to expand the method to determine low energy resonance strengths in proton capture processes.

The TAMU group has prepared a white paper making a case for increasing both stable and radioactive beam capabilities by re-activating the 88" cyclotron. As a driver for production of radioactive isotopes in the MARS spectrometer, and for re-acceleration in the K500, it would allow high quality radioactive beams of both neutron-deficient and neutron-rich isotopes in the 5 to 50 MeV/u range. The expanded range of stable and radioactive beams would create an exceptionally versatile facility at modest cost, and could also play an important role in RIA development projects. It should be noted that such an upgrade would provide capabilities and opportunities far beyond what the local TAMU group could address. This would require a restructuring of the operations at the Cyclotron Institute to bring it more in-line with a national user facility.

### 4.1.5 TUNL

The base research program at the Triangle Universities Nuclear Laboratory (TUNL - consisting of Duke University, the University of North Carolina and North Carolina State University) addresses a broad range of scientific questions. The precision measurements of few-nucleon cross sections and analyzing powers has a long history at TUNL, and will continue for several more years. This program relies heavily on the unique capability of the laboratory for studying polarization phenomena, both with intense polarized beams, but also with polarized targets.

The astrophysics program at TUNL is characterized by several somewhat independent initiatives that utilize the full range of experimental opportunities the TUNL laboratory has to offer. The nuclear astrophysics group at the University of North Carolina pursues a very rigorous experimental program at the newly constructed LENA facility, which consists of two high intensity low energy accelerators. The experiments at this facility focus on the study of proton capture reactions at extremely low energies to investigate the reaction mechanisms and resonances in reactions of the CNO, NeNa, and MgAl cycles. These studies have great promise for improved understanding of nucleosynthesis in main sequence stars, hydrogen shell burning during late stellar evolution, and nova nucleosynthesis. The LENA capture experiments are complemented by transfer reaction measurements at the TUNL FN-tandem accelerator which probes the respective compound nuclei at an excitation range around the proton threshold. This approach provides a unique tool for searching for and identifying low energy resonances not accessible in direct measurements. Parallel to these local efforts, the group is also involved in radioactive beam measurements at the HRIBF facility at ORNL. It should be noted that the group works in close collaboration with theoretical astrophysicists world-wide on improving the nuclear astrophysics data tables and also in improving the theoretical models for a broad range of nucleosynthesis processes.

A complementary program has developed at Duke university using the newly installed HI$\gamma$S facility at Duke. This effort centers around the use of high energy photons for measuring $\gamma$-induced processes at stellar conditions. A first measurement focused on the $^2$H($\gamma$,n)$^1$H reaction, which is of fundamental interest for big-bang nucleosynthesis and needs to be determined with high accuracy. A more extended astrophysics-related experimental program is under development.

The TUNL facility has a strong educational component, with a large number of graduate students, and some common instructional efforts that benefit all of the member universities.

#### 4.1.6 University of Washington

The nuclear physics program at University of Washington (UW) is coordinated through the Center for Experimental Nuclear Physics and Astrophysics (CENPA). The research program includes outstanding programs in neutrino research, principally at the Solar Neutrino Observatory (SNO), and precision studies of the gravitational interaction. The group is also actively involved in a proposal for a new US underground science facility. Low energy nuclear physics research at UW has utilized the FN Tandem accelerator at CENPA. The group has recently "moth-balled" its superconducting booster linac in order to focus on nuclear astrophysics measurements and studies of the weak interaction.

For the nuclear astrophysics experiments the Tandem accelerator is operated in single-ended mode and run at very low energies. Recently the group has focused on measurements of reactions of the pp-chains in solar hydrogen burning. In particular, they have recently completed a new high precision measurement of the $^7$Be(p,$\gamma$)$^8$B, which is important in interpreting measurements of the high energy neutrino flux from the sun. They are also undertaking a careful measurement of the neutrino spectrum from $^{8}$B decay because of its importance in understanding the new data expected from the SNO experiment.

For the future the group proposes to extend the measurements of $^{7}$Be(p,$\gamma$)$^{8}$B to lower energies, measure the $^{3}$He($\alpha,\gamma$)$^{7}$Be cross section that feeds the pp-II- and pp-III-chains in the sun, and complete a series of precision beta-decay studies searching for new terms in the elementary weak interaction.

### 4.1.7 Yale University

The research program in nuclear structure at Yale has recently been renewed, with the construction of several new instruments and spectrometers. The program centers on four broad topics: 1) Structural evolution, phase transitions, and critical point behavior in finite nuclei. 2) Collective modes, including new studies of several types of phonon and multi-phonon excitations, whose structure reflects the interplay of collectivity, single particle motion, and the Pauli Principle; 3) Proton-neutron correlations, including chiral bands, the shears mechanism, quasi-deuteron states in N=Z nuclei, and mixed- symmetry states; 4) Exotic nuclei, with experiments at HRIBF and ISAC, and the development of new, highly efficient, signatures of structure. The research is carried out mostly at the local Tandem using the new instruments, with complementary work at other facilities.

Nuclear astrophysics at Yale has a long-standing tradition. Over the last decade the group has developed a strong program using ATLAS at ANL and the HRIBF at ORNL and pioneered and participated in all of the experiments using $^{17}$F and $^{18}$F beams at HRIBF for nucleosynthesis measurements in the hot CNO cycles. The group has recently become heavily involved in the radioactive beam program at ISAC/TRIUMF, participating in the study of reactions for the hot NeNa-cycle. Locally the group developed a strong complementary program at the Yale Tandem accelerator. This program aims at probing the level structure of neutron deficient isotopes near the particle thresholds using light and heavy ion transfer and charge exchange reactions. This results in important information about level structure and level energies within the Gamow window of explosive nova and X-ray burst nucleosynthesis in the CNO-, and NeNa cycle range. Another focus is the study of break-out reactions from the hot CNO cycles triggering the rp-process. These complementary techniques are important for guiding the direct capture studies at radioactive beam facilities like HRIBF/ORNL, ISAC/TRIUMF, or at RIA in the future.

## 4.2 NSF Facilities

The National Science Foundation maintains four heavy-ion accelerator facilities for low-energy nuclear physics research, located at Florida State, Michigan State, Notre Dame and the State University of New York at Stony Brook. The recently upgraded Michigan State Superconducting Coupled Cyclotron accelerator operates as a national user facility, while the remaining programs are local university laboratories. Research at these facilities spans the full range of low-energy physics, from weak interactions and structure to nuclear astrophysics and reactions. The NSF university laboratories play a vital role in the low-energy nuclear physics field, not only for their research productivity, but as a source of training for young investigators.

**Michigan State University** Until the completion of RIA, the Coupled Cyclotron Facility (CCF) at NSCL will serve as the premier accelerator in the United States for producing fast fragmentation radioactive beams for nuclear research. The accelerator complex injects high charge-state, high intensity beams of all elements into a K500 superconducting cyclotron that is coupled to a K1200 superconducting cyclotron. Representative beam capabilities are projected to extend from $^{40}$Ar ion up to energies of 160MeV/A with intensities of order 0.5 p$\mu$A to $^{238}$U at 100 MeV/A and 0.1 p$\mu$A. Both stable and radioactive beams are available from the complex. For radioactive beam production, stable beams from the K1200 are directed onto a target for the production of fast fragmentation beams containing a broad distribution of reaction products. These are separated in the A1900 beam analysis system, equipped with beam tracking and particle identification detectors for isotope tagging. To accommodate the needs of the user community, several major detector capabilities are presently in operation or under construction. The S800 magnetic spectrograph is a high resolution ($E/dE \sim 10,000$), large solid angle (15-20 msr) device with a 10% energy acceptance. Charged particle arrays include the MSU $4\pi$ array and the portable Miniball, plus a 92-inch scattering chamber for mounting other such arrays. For experiments that require neutron detection, a portable liquid scintillator neutron wall (2mx2m) is available for low-energy coincidence studies and the Superball liquid scintillator tank is used as a neutron multiplicity meter in conjunction with charged particle arrays. An RPMS Wien filter system occupies another beam line.

Major new equipment will include 18 32-fold segmented germanium detectors that will allow nuclear spectroscopy studies of high velocity beams. A large gap superconducting sweeper magnet is under construction for studies of neutrons at zero degrees and for coupling with the S800 (in collaboration with Florida State). A collaboration of ten smaller universities has recently been funded to construct a position sensitive neutron wall that will have an efficiency five times that of existing walls. Another collaboration with Washington and Indiana Universities is developing a high granularity, large dynamic range charged particle array based on silicon strip technology and chipset electronics.

Two additional major development projects that are directly related to RIA R&D are also underway. A high pressure gas stopping cell/ion guide system is being constructed to provide a low energy beam line that will be equipped with a 9.4 Tesla Penning ion trap for mass measurements and can also be used for laser spectroscopy and nuclear structure studies. A program of superconducting cavity development has successfully produced two single cell units and a multiple cavity cell is under construction.

The major recent research highlight of the MSU facility has been the successful completion and initiation of the experimental program on the CCF in the summer of 2001. In the initial studies a $^{33}$Al beam was prepared and subsequently used to measure its half-life and perform Coulomb excitation studies. Several significant results were obtained by the MSU faculty prior to the two-year upgrade shutdown. A representative sample of the extensive output from the laboratory includes: evidence for a subshell at N = 32, results suggestive of isospin fractionation in heavy-ion collisions, transverse flow measurements that showed the transition from attractive nuclear flow to repulsive flow due to high pressure, and $\alpha + \alpha$ cross section measurements relevant to lithium synthesis in the early universe

The scientific program presently focuses on questions of nuclear structure and dynamics far from stability and carries a strong astrophysics component. The unique capabilities of the facility will be used to study directly decay and reaction mechanisms for nuclei along the rp- and the r-process path in the lower mass range. These experiments will help to develop the techniques necessary for the experimental astrophysics program at RIA. The operation of the facility will also be particularly important to address the technical and experimental problems associated with the fragment separated beams from RIA.

**Florida State University** Florida State University conducts a diverse program with a local emphasis on structure and reaction mechanisms. The accelerator facility consists of a 9MV tandem plus superconducting linac that produces stable beams ranging from hydrogen up to nickel ions with energies up to 10 MeV/A. Unique features of the facility are a dedicated $^{14}$C source and an optically-pumped polarized $^{6,7}$Li source. At present the laboratory is constructing a radioactive beam system that will accelerate beams of $^{14}$O and $^{18}$F. Nuclear spectroscopy measurements are conducted with a gamma-ray array consisting of three clover and 12 single crystal germanium detectors. A laser system exists for the study of atomic structure.

Research highlights obtained with the FSU accelerator include the first measurement of a complete set of rank 3 analyzing powers for $^{7}$Li scattering and use of the $^{14}$C($^{14}$C,p)$^{27}$Na reaction to complete the first level scheme measurements for a T = 5/2 sd shell nucleus. The group also plays a strong role in the Gammasphere research program and is involved in collaborative experiments at MSU/NSCL, Jefferson Laboratory and RHIC.

**University of Notre Dame** The University of Notre Dame operates three Van de Graaff accelerators, of class JN, KN and FN, to study a wide range of problems in nuclear astrophysics, weak interactions, nuclear reaction mechanisms and structure. The unique operating capability at Notre Dame is the TWINSOL facility, which employs a dual solenoid/electrostatic separator to produce radioactive isotope beams. Low-energy beams of $^{6}$He, $^{7}$Be, $^{8}$Li, $^{8}$B, $^{14,15}$O and $^{17}$F have been accelerated at intensities of $10^4 - 10^6$ particles/s. Primary detector apparatus includes several gamma-ray detectors, including several 55% efficient germanium detectors and a pair of Ge clover detectors, a general purpose scattering chamber and ancillary detector systems.

Nuclear astrophysics research has focused on several areas, e.g. the CNO cycle, break-out reactions from the CNO cycle, reaction rates for the rp process, reactions in stellar helium burning and the s-process. Structure studies have been performed with radioactive beams using TWINSOL to investigate the level structure of $^{66}$Zn. As part of the reactions program, the emphasis has been on sub-barrier fusion reactions with $^{6}$He and studies of the proton-halo nucleus $^{8}$B. The $\beta$-decay of $^{8}$B and the associated neutrino spectrum has been studied in order to search for new components of the electroweak interaction. The Notre Dame faculty are also active users of numerous other facilities, including the DOE low energy facilities, NSCL/MSU and many other facilities world-wide.

**State University of New York at Stony Brook** The Stony Brook program emphasizes weak interaction physics with laser-trapped Fr atoms and nuclear structure at high spin. These experiments utilize a 9 MV tandem accelerator coupled to a superconducting linac capable of 10 MeV/A for light ions and 6 MeV/A for $A < 90$. To meet the specialized needs of the Fr research program, the linac is capable of 0.5 p$\mu$A beams of 100 MeV oxygen and fluorine ions, in order to generate a secondary beam of low energy francium ions of intensity $10^7$/s. The francium beam is subsequently focused by a series of electrostatic lenses into an atom trap for weak interaction studies.

Research with the trapped Fr atoms at Stony Brook is a unique project that utilizes a significant fraction of the accelerator time. There is also a strong atomic physics component of this program. Isotopes of $^{208-212}$Fr have been trapped and studied thus far as part of an effort to make systematic measurements of these radioactive alkali metal atoms. At this stage, the group has reached a quantitative understanding of the atomic structure of Fr and is preparing a systematic study of the anapole moments.

The structure program is primarily conducted using Gammasphere with a strong local component with in-house gamma-ray facilities. Recent work has been on band termination in the mass 110 region, and the Stony Brook group has also led the effort to discover and characterize chiral bands.

## 4.3 Non-US facilities

Research efforts in nuclear structure physics and astrophysics are carried out world-wide with a similar science focus as in the US. The main facilities that compete and complement the present US program are found in Canada, Europe and Japan. In Canada the effort is focused in the ISOL-based radioactive beam facility ISAC, which is providing beams of light radioactive isotopes up to an energy of 1.5 MeV/A, mainly for astrophysics studies. No major facility based solely on stable beam operations is available presently in Canada. In Europe, the effort on nuclear structure physics and astrophysics is carried out in several national facilities that employ both stable and radioactive ion beams over a broad energy range. A major effort is underway in Europe to construct two types of radioactive beam facilities, one relying on the high-energy fragmentation technique, proposed by GSI and operating up to 1.5 GeV/A beam energy, and the other based on the ISOL concept, i.e. the EURISOL project. In Japan the main effort is spent on the operation and construction of the RIKEN facilities for fast radioactive beams, with some effort on low-energy nuclear physics in Osaka.

**Canada** The Isotope Separation and Acceleration (ISAC) facility at TRIUMF is presently starting operation and the first radioactive beam test experiments with $^{21}$Na have been successful. ISAC will soon provide one of the major opportunities for experiments with low-energy radioactive beams in the fields of nuclear physics, astrophysics, materials science and nuclear medicine. It offers an interesting opportunity for US users prior to construction of RIA. ISAC employs a 500 MeV proton beam coupled to a thick target and ion source ISOL system. It is therefore expected to be able to produce high-intensity beams of both neutron-rich and neutron-deficient nuclei over the entire nuclear chart. The phase I ISAC post-accelerator will be able produce all these beams at keV energies and with 1.5 MeV/A energy for ions up to A=30. The recently approved upgrade ISAC II will extend the mass range of ions up to A=150 and the final energy is increased to about 6.5 MeV/A. The ISAC II acceleration scheme utilizes the existing RFQ and a new pre-stripper drift-tube linac coupled to a superconducting linac for the post-stripper section. The ISAC II upgrade is planned to become operational in 2005-2007.

There are clear opportunities for the US low energy nuclear physics community to become involved in several projects both at the technical and physics levels. Physics experiments both for ISAC I and II offer first-hand experience both to sustain and build a future US community to fully exploit RIA. US teams would also benefit from involvement in both the target-ion source and accelerator developments of ISAC II and associated experimental instrumentation.

**Europe** In low-energy nuclear physics, Europe provides several small university or medium scale national facilities. Thirteen such facilities are now operating under the umbrella of the European Union, which provides direct support for the access of users to these facilities. In its 1997 Long Range Plan NuPECC emphasized the need for a network of stable beam facilities to complement the science to be done with radioactive beams. Those facilities are GSI with its UNILAC accelerator and the 18 Tm synchrotron; GANIL with its coupled cyclotron facility; the tandem-linac combination (ALPI) in Legnaro (Italy); the tandem accelerator Vivitron in Strasbourg (France); the sites of the EUROBALL gamma-ray array; the heavy ion cyclotron at Jyväskylä (Finland); the superconducting cyclotron in Catania (Italy), and the superconducting cyclotron AGOR in Groningen (The Netherlands). In eastern Europe additional opportunities exist at the Flerov Institute in Dubna (Russia) where two U400 cyclotrons provide heavy ion beams over a broad energy range. All these facilities carry out low-energy nuclear physics studies on structure and reactions with increasing emphasis on the studies of nuclei far from the valley of stability.

Several accelerator centers are now operating or under development that are focussed on radioactive beams. At the high energy regime GSI and GANIL are already producing beams by fragmentation reactions at 1 GeV/u and 70 MeV/u, respectively. Presently GSI can produce beams up to uranium and GANIL up to Sn. At low energy, the ISOL-type pilot facility at Louvain-la-Neuve has been operating since 1989, focusing on nuclear astrophysics in the light-element sector. There is a broad range of the first generation ISOL facilities in the design or construction phase using a variety of driver and post accelerator combinations. The SPIRAL facility at GANIL employs the heavy-ion fragmentation reactions coupled to a K=265 MeV cyclotron post accelerator. It has now become operational, has delivered its first beam, $^{18}$Ne, and will be able to provide radioactive beams up to about A=70 near or above the Coulomb barrier. The ISOLDE/CERN facility (Switzerland) provides the site for the

REX-ISOLDE experiment. ISOLDE employs 1.4 GeV protons from the PS Booster and produces intense beams of radioactive ions of about 70 elements and 700 isotopes. The REX-ISOLDE setup relies on a novel charge breeding concept based on a coupled Penning trap and an electron beam ion source together with a 2.2 MeV RFQ linac system as a post accelerator. The charge breeding concept has been demonstrated to work with a nearly 10% efficiency to reach the needed m/q ratio of 4-5. The first experiments employing a neutron-rich $^{26}$Na beam have recently commenced.

In addition, there are several projects in the planning or construction stage. They include the EXCYT project at the INFN/LNS in Catania (Italy) that is based on a cyclotron as a driver and a 15 MV tandem post accelerator; the MAFF (Munich Accelerator for Fission Fragments) project is using the high-flux reactor (FRM-II) as a driver and a linac post accelerator; the proposed SPES project in Legnaro (Italy) utilizing a 10-100 MeV/A p/d linac as a driver and the existing ALPI accelerator for post acceleration; the proposed upgrade of SPIRAL to include fission product beams at GANIL (France), and the proposed CASIM project at Daresbury (UK) utilizing the 200 MeV $H^-$ cyclotron as a driver and the superconducting linac as a post accelerator.

Following the recommendation of the Long Range Plan of NuPECC(1997), several R&D efforts have been initiated in order to improve the overall concepts for radioactive beam facilities as well as to provide strong basis for the forthcoming second generation facilities. The overall R&D support from the EU alone is of the order of 15 M$ in the period of 1998-2004. These R&D projects have dealt with topics such as gamma-ray tracking, focal plane detectors, ion cooling and trapping, instrumentation for fragmentation experiments, high-power targets and ion sources, gas catcher technique and charge breeding.

Concerning the future second generation radioactive beam facilities, two options are being investigated or proposed in Europe. GSI has submitted a proposal to become a major international facility that takes into account the broadened scope of the physics of the strong interaction and in fundamental many-body systems. The new facility consists of a 100/200 Tm synchrotron double-ring and a system of associated rings for beam collection, cooling, phase space optimization and experimentation. A key feature of the facility will be the generation of intense, high-quality secondary beams, in particular beams of short-lived nuclei and anti-protons. For radioactive beam production the goal is to produce primary ion beams of all elements from hydrogen to uranium with intensities that are up to two orders of magnitude larger than the present ones, i.e. more than $10^{12}$ ions/s. In this high-intensity mode, the beam energy is variable up to 1.5 GeV/u. The proposed exotic-nuclear-beam facility consists of a super-conducting two-stage fragment separator (Super-FRS) that serves the double storage ring system, Collector Ring (CR) and New Experimental Storage Ring (NERC), including an intersecting electron ring (eA collider), as well as high- and low-energy experimental areas.

Another concept under development is the ISOL-based facility EURISOL. This site-independent EU-funded R&D project has the objective to prepare a conceptual lay-out of the second generation ISOL-based radioactive ion beam facility, to identify synergies and R&D needs on key technologies as well as to establish a cost estimate for such a facility. A report on this project, involving ten European laboratories and coordinated by GANIL, is due in September 2002.

These European projects offer real opportunities for collaborative efforts with US scientists within a wide range of topics from the lowest energies to fragmentation. In fact, several collaborative efforts are already underway, including the the gas-catcher project, which is a collaboration of nine institutions led by Argonne.

**Japan** Low-energy nuclear physics and nuclear astrophysics in Japan is mainly carried out in two facilities at Osaka and RIKEN in Tokyo. The Osaka University (RCNP) operates a K400 cyclotron for high-resolution experiments on nuclear structure and reactions. At present RIKEN has a heavy-ion accelerator complex consisting of a K540 ring cyclotron (RRC) and several different types of the injectors: a variable-frequency Wideroe linac and a K70 cyclotron.

To develop further these fields of science, the RIKEN Accelerator Research Facility (RARF) has undertaken construction of a Radioactive Ion Beam Factory (RIBF) as a next generation facility that is capable of providing the intense Radioactive Ion (RI) beams over the full range of atomic masses. The new facility will add new dimensions to the RARF's existing capabilities mentioned above. Moreover, its projectile-fragment separator (RIPS) provides intense light-atomic-mass RI beams. In the factory, a cascade of a K520 fixed-frequency ring cyclotron (fRC), a K980 intermediate-stage ring cyclotron (IRC) and a K2500 superconducting ring cyclotron (SRC) will be a post-accelerator for the existing RRC. This new cyclotron system will be able to boost the RRC's output energy up to 400 MeV/nucleon for light ions and 350 MeV/nucleon for very heavy ions. The goal of the beam intensity is higher than $1 p\mu$A. As in the existing RIPS, RI beams will be generated mostly by projectile fragmentation. In addition, fission of a uranium beam will be used for the production of very neutron-rich isotopes in the medium mass region. A BigRIPS will be installed to generate RI beams with much larger magnetic rigidity. The RIBF includes the multi-use experimental storage rings (MUSES) consisting of an accumulator cooler ring (ACR) and an electron-RI beam collider. MUSES will allow various types of next-generation experiments: electron scattering on unstable nuclei, precision mass measurements, and atomic physics with cooled electron beams. In the original MUSES project, ion-ion merging or head-on collisions and X-ray spectroscopy of unstable nuclei are also planned.

The fact that RARF will become operational in 2005 could make participation in the RIKEN program very attractive to the US community.

# 5 New Initiatives

Several important new initiatives have been identified in Low Energy Nuclear Physics as outlined in the 2001 NSAC Long Range Plan. These include the Rare Isotope Accelerator (RIA), which is recommended as the "highest priority for major new construction" and a major new national gamma-ray detection facility based on the novel concept of gamma-ray tracking. A brief introduction and discussion of essential research and development issues presently relating to RIA and the gamma-ray tracking detector are contained below.

## 5.1 RIA and essential R&D

The construction of the Rare Isotope Accelerator, RIA, has been identified in the 2001 NSAC long range plan as the highest priority construction project for the nuclear physics community. The basic RIA concept was developed by the NSAC ISOL Task Force (the Grunder Committee) and has been discussed in the final report of that committee. The present RIA concept is an evolution of the Advanced ISOL Facility that was endorsed in the 1996 Long Range Plan, together with the NSCL upgrade, as the highest priority for new construction by the nuclear physics community. While the RIA project has not undergone a formal cost and operations review, the total project cost is estimated to be about 800 M$ with an annual operating budget of 75 M$. This cost design has been reviewed by the Harrison committee and was judged in the report to NSAC as "essentially stable" and within scope.

The RIA concept utilizes both projectile fragmentation and ISOL techniques to optimize the variety of high intensity radioactive beams available. This is a novel concept that offers a range of scientific opportunities far beyond those available at existing or proposed facilities world-wide. The construction of RIA based on this concept would ensure a leading role of US nuclear science for several decades. However, the construction and operation of RIA pose formidable technical challenges to the community that must be addressed by a strong R&D program.

The RIA design is centered around a heavy ion multi-beam LINAC driver accelerator formed by short, independently-phased, superconducting rf cavities and providing 400 kW beams from hydrogen up to Pb at energies $\geq$400MeV/u. New concepts in ECR source technology would allow Uranium beams up to 400 kW by producing up to $30^+$ U ions with high intensity feeding into an RFQ injector and the subsequent low-$\beta$ acceleration stage. Final acceleration is provided by a sequence of stripper sections and medium-$\beta$ and high-$\beta$ superconducting LINAC stages. The secondary radioactive isotopes are generated in the production target by a flexible range of reaction mechanisms: projectile fragmentation, projectile fission, target spallation, and target fragmentation. Production can be further enhanced by neutron-induced fission techniques. Fast secondary beams ($\leq$500 MeV/u) are typically produced by in-flight fragment separation and will be available for experiments in a high energy area.

A wide range of experimental techniques is being developed and optimized at the Coupled Cyclotron Facility at NSCL/MSU, which already provides a large range of lighter mass fragment-separated radioactive beams for the nuclear physics community. Low energy radioactive beams can be generated by ISOL techniques by target spallation or fragmentation. The RIA concept utilizes the alternative technique of gas-stopped fragment-separated beams to optimize the production rate for a wide range of isotopic species. The radioactive species are extracted as low energy ions ($\leq$100keV) that can be studied using trapping via laser spectroscopy techniques, or alternatively post-accelerated up to 1MeV/A for low energy astrophysics experiments. They can be further accelerated with a second post-accelerator LINAC to $\leq$15MeV/A for nuclear structure and reaction physics experiments.

The technical realization of RIA depends on the immediate availability of funds to support significant R&D on accelerator and target technology as well as on experimental techniques and equipment. RIA R&D includes the test of critical new technologies to assure optimum performance. It also includes the development and prototyping of RIA sub-systems (for example accelerator modules) prior to the production and assembly phase to assure cost and schedule requirements can be met. RIA R&D also includes tests for critical components that may affect or limit the general performance of the facility, such as the high power target systems, the gas-stopper design, and the extraction and ion-source systems. Finally, RIA R&D includes the development and optimization of experimental methods and techniques, as well as the development of detectors, recoil separators and data handling systems.

An impressive collaborative effort for RIA R&D has already been developed at US, Canadian, and European laboratories addressing a wide range of critical components. The national RIA R&D program is coordinated for the DOE by the Marx Committee, which is responsible for providing guidance in the allocation of available funds. Many of the DOE- and NSF-funded national laboratories and facilities are involved in RIA R&D. One key effort is focused on the source for the RIA driver accelerator. The overall intensity for RIA beams is limited by the efficiency of the primary ECR source. The heaviest beam for the RIA driver is uranium at a charge state of $30^+$ and an intensity of $4\text{x}10^{13}$/s for injection into the RFQ. These requirements are most demanding in terms of ECR source performance. A prototype for the RIA ECR source is the VENUS ECR source under construction at LBNL. A second major effort is focused on accelerator design. ANL has an intense research program focused on the development and design of the driver LINAC drift tube cavities as well at the RFQ post acceleration structure for astrophysics experiments. Jefferson Laboratory also participates in the development and testing of drift cavities for the high $\beta$ section of the driver LINAC. Efforts in developing a windowless liquid lithium target for the heavy uranium beams are presently underway at ANL.

Particular attention is also necessary for the subsequent gas catcher and ion guide design for stopping the fast fragmentation products. Again both ANL and NSCL collaborate on developing and testing the necessary components. Test experiments for gas stopping are being performed at the GSI heavy ion accelerator in Germany. Target release studies for ISOL beams are presently performed at the HRIBF facility at Oak Ridge National Laboratory, which is also involved in the development of improved ECR source designs for the secondary beams. Further developments at HRIBF include a time-of-flight system for isobar separation of reaction products.

RIA also needs to be fully outfitted with state-of-the-art detector and magnetic separator equipment to address the wide range of proposed experiments. Development of the necessary equipment and of experimental expertise for RIA is a crucial part of the RIA R&D effort.

Existing facilities in Europe and on the North-American continent offer broad opportunities that are increasingly utilized by the community. The HRIBF facility at Oak Ridge is based on the ISOL concept. It is a prime site for the development of experimental equipment using a variety of neutron-deficient and neutron-rich radioactive beams for nuclear astrophysics and nuclear structure studies. An alternative is Canada's ISAC facility at TRIUMF, which promises a wide range of ISOL-produced, lower energy, post-accelerated beams for nuclear astrophysics measurements. The DRAGON separator for recoil detection provides an outstanding opportunity for probing the limits of nuclear astrophysics experiments with radioactive beams. The coupled cyclotron facility at the NSCL/MSU on the other hand offers optimal conditions for developing experimental techniques and methods for fast fragmentation-based radioactive beams.

### 5.2 Gamma-Ray Tracking

In all fields of scientific endeavor, important discoveries are often made by capitalizing on promising breakthroughs in technology. An example is provided by the major advances in gamma-ray detection devices culminating in Gammasphere in the US and Euroball in Europe. The influence of these arrays has been enormous and the data they are providing is leading to a vastly deeper understanding of the rich structure and behavior of the atomic nucleus. Gammasphere was the first national gamma-ray facility in the US (1995) and will continue to have a profound impact on nuclear structure research for many years to come as a prime focus for the US and world-wide nuclear structure community.

While the present state-of-the-art detector arrays, which consist of large volume germanium crystals surrounded by a suppression shield, have pushed this particular detector technology to its limit, it has become apparent that significant further gains in sensitivity will be possible as a consequence of an innovative and new design paradigm utilizing the concept of gamma-ray energy tracking in electrically segmented Ge crystals. These new opportunities have arisen from technical innovations made by the highly successful Gammasphere collaboration. The detector concept, which was mentioned in the 1996 Long Range Plan is called GRETA (Gamma-Ray Energy Tracking Array). It would contain about 100 co-axial Ge crystals each segmented into 36 portions and arranged in a highly efficient $4\pi$ geometry. It is anticipated that GRETA would have $\sim$ 100-1000 times the sensitivity of Gammasphere for selecting weak exotic signals while being of similar overall cost.

In addition, a detector technology based on segmented planar (strip) germanium detectors is also being actively pursued. Arranged into a box-like configuration, the GARBO (GAmma-Ray Box) design will be especially efficient for low-energy gamma rays and x-rays and is therefore an important complementary detector system rather than an alternative to the $4\pi$ coaxial detector array described previously.

The improved sensitivity is due to the new technique of "tracking", which identifies the position and energy of gamma-ray interaction points in the detector segments. Since most gamma-rays interact more than once within the crystal, the energy-angle relationship of the Compton scattering formula is used to "track" the path of a given gamma-ray. The full gamma-ray energy is obtained by summing only the interactions belonging to that particular gamma-ray. In this way there are no lost scatters into suppression shields (which cover nearly 50% of $4\pi$ in Gammasphere) and so a much higher overall efficiency can be achieved. Other key design benefits of a highly segmented Ge array include high energy resolution, high counting rate capability, good position resolution which is critical for Doppler shift corrections since many experiments involve high recoil velocities, the ability to handle high multiplicities without a high double-hit probability, and the ability to pick out low-multiplicity events hidden in a high background environment. Of course, any final design would be optimized to take advantage of coupling with auxiliary detector devices, which continue to prove themselves of such value in Gammasphere and other gamma-ray experiments.

Many detailed R&D projects have been carried out since the 1996 LRP on all the main ingredients necessary to show that building a tracking detector array is now feasible. The Europeans have enthusiastically embraced this new technology, have made similar tests, and are moving ahead with plans to build a $4\pi$ highly segmented Ge shell. In this country, numerous workshops have been held to discuss the compelling physics opportunities gamma-ray tracking detector systems would bring, as well as technical workshops from which working groups have been formed. A national Gamma-Ray Tracking Steering Committee has been established in order to coordinate the US effort.

The US nuclear structure community, which conceived of this next revolutionary step in gamma-ray detection capability, is therefore poised and eager to build a new generation of gamma-ray spectrometer with unsurpassed sensitivity. Of course necessary research and development still remains, for example, to obtain a three cluster module (which forms the basic "unit cell" of the system) and to perform cross crystal scattering tests, to prototype and test new digital readout electronic modules, to develop more advanced tracking algorithms, etc. While this work will carry on, there appear to be no technical show stoppers to building a $4\pi$ tracking detector.

Such tracking detector systems will enable new classes of high resolution gamma-ray experiments in nuclear structure, nuclear astrophysics, and weak interactions at existing facilities and will become a flagship instrument at RIA. Such revolutionary technology will have enormous benefits for the broader low energy physics community both prior to and during the RIA era, while holding the promise of important spin-off applications in other fields, such as, medical, environmental, security, and space exploration.

# 6 Subcommittee Findings

The charge to the subcommittee (see Appendix B) requests that we address three questions posed by the funding agencies in the original charge to NSAC:

1. What scientific opportunities should be addressed and what facility and instrumentation capabilities should be used and developed, including those supported by NSF and outside the United States, in order to maintain a strong scientific program in the coming decade?

2. What opportunities can be pursued with funding at the FY 2002 Budget Request level ($52.7 million) and an assumed constant level of effort into the out-years? What is the appropriate mix of facility operations, research, investments in instrumentation and RIA R&D that will be needed to optimally exploit these opportunities?

3. What are the priorities of the scientific opportunities that could be pursued with additional funds beyond this constant level of effort?

We will address each of these questions below. We note that the first question is very broad, and includes addressing programs beyond the existing DOE Low Energy Nuclear Physics Program. While the committee heard presentations from the NSF low energy facilities and from representatives of facilities in Europe, Japan and Canada, the bulk of our deliberations focused on the DOE facilities. Thus we will respond to this first question in broad terms, but present specific recommendations to the remaining questions, focused on the DOE Low Energy Nuclear Physics Program.

Before presenting our recommendations, it is useful to discuss some of the issues that led to our findings. In our interactions with the low energy nuclear physics community two issues were identified by the community as very important to the future direction of the field. We present these issues in the next section. Also, in attempting to formulate a detailed response to the above questions, the subcommittee found it useful to identify a set of *Guiding Principles* that helped form the basis of our recommendations. These principles reflect input we received from the facilities and the community as well as our own deliberations, and are presented below.

## 6.1 Issues Facing the DOE Low Energy Physics Program

**Funding** The funding level for the DOE Low Energy Nuclear Physics Program's national user facilities at ANL, ORNL and LBNL, as well as at the university-based facilities, has been approximately constant during the past three to four years. The cost of living increases during these years have seriously eroded the support for the research programs at these facilities, resulting in a reduction of both the staff and beam operations. All of the low energy facilities are delivering beams for research at levels well below optimum (by as much as $\sim$ 50% !). The accelerators at ANL and ORNL are shut down on weekends, while LBNL plans operation for only 25 weeks in FY02. The cost savings in reducing operations from 7 to 5 days per week operation are only $\sim$ 10%, but the loss in beam availability for research is over 30%. As a result, experiments with excellent scientific ratings are under considerable beam-time pressure, and other high-quality experiments cannot even be conducted. A 15% increase in the funding level of the low energy nuclear physics program is required to operate and utilize the facilities at the optimum level.

**RIA Mission CD-0** A large fraction of the low energy nuclear physics research community is on an exciting research path that will lead to the next-generation RIA facility. This facility has been given the highest priority for major new construction in the FY01 NSAC Long Range Plan. The community is now waiting for the DOE to make a formal determination (referred to officially as CD-0) that RIA is critical to its ability to carry out its basic research mission in Nuclear Physics. The committee notes that approval for CD-0 resides in the Office of the Secretary of the DOE for projects of the scale of RIA. Once this determination has been made it will be possible for this community of about 700 scientists in the US to plan its accelerator and instrumentation development activities and scientific research programs efficiently. It will also help in attracting young physicists into this field. While several young experimental physicists have recently entered this field, there appears to be shortage of young low energy nuclear theorists.

## 6.2 Guiding Principles

The over-riding principle that the subcommittee adopted was a general endorsement of the recommendations of the 2001 LRP. This support for the 2001 LRP thus guided our considerations of both RIA and the utilization of the existing facilities. The Guiding Principles then are:

- **RIA is essential for the vitality of the low energy nuclear physics community.**

  To insure a timely construction for RIA, considerable R&D is essential. The bulk of the funding for RIA R&D comes from the existing Low Energy Nuclear Physics program. Maintaining the momentum for RIA requires a modest increase in the present level of funding for R&D in the near term, and further increases in R&D following CD-0. In addition, new state-of-the-art instrumentation and techniques must be developed in preparation for the RIA era.

- **The low energy nuclear physics community must maximize its scientific output in the pre-RIA era.**

  The Low Energy Nuclear Physics Program should strive for the cost-effective utilization of existing facilities while maintaining enough flexibility to address exciting new initiatives. The community must focus on world-class capabilities provided by accelerators providing both stable beams and radioactive species produced by in-flight fragmentation and ISOL techniques. New experimental instrumentation provides critical capabilities and should be supported as well. Adequate support for the user community and for nuclear theory is essential to reap the benefits of this efficient facilities utilization effort.

- **In preparation for RIA, the low-energy nuclear physics community must be nurtured and maintained.**

  RIA is expected to be a large-scale national user facility capable of supplying beams for a user community comparable in size to those at CEBAF at Jefferson Lab and RHIC at BNL. Given the timescales for projects of this size, it is obvious that many of today's active researchers in nuclear structure and nuclear astrophysics will be unavailable for RIA. Thus the community must capture the imagination of a new generation of researchers and train them in the necessary techniques to take full advantage of the capabilities of RIA. It is the universities that supply the future scientists and the national user facilities that provide the state-of-the-art capabilities for their research. Both university and national user facilities play critical roles in developing the next generation of researchers.

- **The low-energy nuclear physics community will require stable beams beyond the RIA startup.**

  As discussed throughout this report, the low energy nuclear physics community is impressively productive. Most of their results are based on measurements carried out using stable beams. In addition, it is certain that even after construction of RIA critical measurements using stable beams will be required. Furthermore, it is almost certain that measurements and discoveries made with radioactive species will stimulate new programs requiring stable beams.

## 6.3 Scientific Opportunities and Instrumentation Capabilities

Exciting discoveries and critical advances have been made in nuclear structure and nuclear astrophysics over the last several decades. Even though nuclear structure studies have been pursued perhaps the longest of any of the present components of nuclear science, the field remains vital and extremely productive. New discoveries in nuclear structure continue to capture the attention of the entire physics community, and stimulate new research programs. Examples include collective motion, new degrees-of-freedom (e.g. pairing, very high-spin, boson-like behavior ...) and superdeformation. Many of these discoveries were made possible by important advances in technology including new accelerator developments, high resolution gamma-ray spectroscopy and recoil spectrometers.

The key role played by nuclear astrophysics in understanding astrophysical phenomena has grown steadily in recent years. With the deployment of new "grand observatories", with greatly enhanced sensitivity across the electromagnetic and neutrino spectrum, an increasingly larger number of phenomena require understanding the basic nuclear physics processes that power and shape the universe. From big-bang nucleosynthesis, to stellar energy and neutrino generation, to isotopic abundances, to neutron stars, to gamma-ray astronomy, nuclear process play critical roles in astrophysics.

For the past twenty years, both of these fields have realized that there is a new frontier to our understanding of nuclear structure and nuclear astrophysics. This frontier is the exploration of structure and reactions involving radioactive nuclei far from the valley of stability. Early, successful, developments of first generation radioactive beam facilities led to modest intensities of a few selected isotopes. Today a new set of facilities are being actively pursued world-wide to produce higher intensity radioactive beams for a wide range of isotopes. Many of these facilities, including HRIBF at ORNL, NSCL at MSU, ISAC at TRIUMF, the RIKEN complex in Japan, and a variety of programs in Europe are producing (or will be shortly) high quality radioactive beams for nuclear structure and nuclear astrophysics research. The subcommittee recommends that focused programs by US researchers at these facilities should be strongly supported. The programs at HRIBF and ISAC involving ISOL production of radioactive isotopes and NSCL involving in-flight fragmentation radioisotope production are especially synergistic with the technology and the science of RIA, where very high intensity beams even further from stability will be produced.

Lastly the subcommittee came to appreciate that it is essential to maintain sufficient capabilities in the production of stable beams of adequate intensity, energy and range of atomic mass to pursue the high quality physics program that will emerge in nuclear structure and nuclear astrophysics in the RIA era.

## 6.4 Recommendations for Constant Effort Funding

Based on input from the DOE facilities and our own review, it is clear that the DOE facilities do not have the funding to operate anywhere near their full research potential. Operations at some of the facilities have been reduced by $> 30\%$ due to the failure of program funding to keep up with inflation. Several of the facilities are operating so close to the margin of fixed costs that further reductions in "buying power" would result in a virtual cessation of accelerator operations. There are also exciting new initiatives underway within the community, specifically the development of RIA and the construction of a next-generation gamma-ray tracking detector. The inability of facilities supported by the program to operate at their full potential, coupled with the importance of supporting new initiatives that represent the future of the field, has resulted in a wholly unsatisfactory situation for the low-energy nuclear physics community.

After extensive deliberation, the subcommittee came to the conclusion that effective utilization of the DOE facilities, continued support for RIA R&D and continued support for research at the universities and national laboratories represent the top priorities for the Low Energy Nuclear Physics Program. In order to achieve these priorities within a constant effort funding scenario, severe and painful changes in the program are necessary. Specifically, we recommend that if only constant effort funding is available:

- DOE support for operations of the 88-Inch cyclotron at LBNL cease, with phase-out beginning in FY03.

- DOE support for operations of the UW tandem accelerator cease, with phase-out beginning in FY03.

- DOE support of RIA R&D be capped at about 25% above the presently supported levels as long as it is funded within the Low Energy Nuclear Physics Program. This cap does not apply once CD-0 has been granted by DOE for RIA and additional funding (from outside of the present Low Energy Nuclear Physics Program budget) has been obtained.

- Funds made available from the above actions should then be used to increase funding for operations at the remaining national lab and university facilities and to support a modest program of gamma-ray tracking development and eventual construction at the level of about one to two modules per year.

The first recommendation above represents a significant loss to the nuclear physics community. The necessity to discontinue operations at at least one major facility became apparent to the subcommittee once the guiding principles (discussed in the previous section) were adopted. The choice of which facilities to terminate was by no means straightforward. Faced with such a choice, an obvious question to ask is "Why should operations at facility X be terminated?". Based on the input to the subcommittee and its deliberations, there is no good answer to this question for any of the facilities under consideration. While not apparent to all on the subcommittee at the beginning of our deliberations, no significant weakness were identified in any of the programs. To the contrary, all of the facilities presented first-rate science programs and strong justifications for continued operation. However the subcommittee, faced with the poor utilization of the existing facilities (resulting from an erosion in funding due to several years at constant dollars) and the need to support new initiatives, came to the conclusion that facility closures were the only viable solution in the constant effort budget scenario.

In view of this situation, the subcommittee was forced to address a different question: "Why should operations at facility X *not* be terminated?". Faced with this question and much thoughtful discussion a consensus was finally reached. This consensus, based on the *Guiding Principles* discussed above, maximizes both short-term and long-term physics goals for the Low Energy Nuclear Physics Program. The subcommittee believes that the choices it has made allow the community to continue its efforts towards construction of RIA within the next five years while maintaining a highly productive research environment. We believe that the recommendations are robust under a variety of different scenarios for the future of the field including the possibility of considerable delays in the funding of RIA.

Our recommendations for ceasing operations at two of the DOE's low energy nuclear physics facilities will lead to considerable losses to the fields of nuclear structure and nuclear astrophysics. In particular, by closing the 88-Inch cyclotron at LBNL we risk losing one of the key intellectual and technical centers of the field. In addition to its long and illustrious record of accomplishment in low energy nuclear physics, LBNL has spearheaded the development of Gammasphere, one of the most productive devices in the field. They have also been leaders in the motivation and the R&D for the next generation of gamma-ray detectors. Their development of the Electron Cyclotron Resonance (ECR) source, and subsequent improvements have been essential for the productivity of many existing facilities and are essential for the plans for RIA. Indeed, both Gammasphere (as well as the Gamma-Ray Tracking detector R&D) and the ECR source have benefited tremendously from the unique range and quality of technical resources (in areas such as superconducting magnet technology and advanced electronics) available at one of our premier national laboratories, and not accessible at university-based facilities. The 88-Inch cyclotron, despite its age, has an excellent record of operational efficiency and is providing much-needed beams for a research program that has broad impact, and the research staff at this facility includes some of the best scientists in the field. If DOE support for the 88-Inch Cyclotron must end, it is essential that this group continue its research as users, and that the ECR R&D continue to be supported.

The University of Washington facility has also had a significant impact on the field, even as the group there has moved its focus away from accelerator-based studies. In addition, the infrastructure associated with the facility has played a significant role in the world-class program of neutrino physics and gravitational studies that forms the bulk of their research program.

Finally, we note that both of these facilities are located at two of the premier research universities in the country, and that ceasing operations of their facilities could result in some of the "best and the brightest" of the next generation of graduate students not choosing nuclear physics for their research careers.

## 6.5 Recommendations for Funding above Constant Effort

Additional funding, above a constant effort budget, would lead to enormous opportunities for the fields of nuclear structure and nuclear astrophysics. A common theme in the facility presentations was that a modest funding increase (at about the 15% level) would allow all of the DOE facilities to attain nearly optimum operational levels. Thus we considered a scenario where the DOE low-energy nuclear physics budget was increased by 15% above FY01 levels. Within this scenario we identified a prioritized list of opportunities that would become available for nuclear science:

1. Restore operations at the 88-Inch Cyclotron at LBNL. This requires about 5 M$ of addtional funding and would allow an outstanding program of heavy-element chemistry and nuclear physics, gamma-ray spectroscopy for nuclear structure, weak interaction studies, and development of a few specialized, high-intensity radioactive beams to be realized. It would also provide important opportunities for graduate students at a premier university to become involved in low-energy nuclear physics research at their home institution.

2. Increase funding for RIA R&D beyond the +25% cap recommended for the constant effort scenario above. In order to proceed with a timely construction of this major facility, significant R&D expenditures will be necessary. The committee charged with identifying the required R&D costs (the Marx Committee) has

recommended a funding at level about three times the present DOE support. With a 15% increase the low-energy nuclear physics budget could support RIA R&D at a level about a factor of two above present DOE support.

3. Increase funding for development of a new gamma-ray tracking detector. Within this scenario, after several years of development work, construction could begin at the level of about five to ten modules per year.

4. Restoration of operations at the UW tandem accelerator for a limited program (2-4 years) of critical experiments in nuclear astrophysics and weak interactions.

5. Further increase operations support, above the constant effort scenario presented above, at all of the DOE facilities. An additional $\sim 5\%$ increase is feasible within the 15% increase discussed above and would allow the facilities to achieve optimum and effective utilization.

# A Charge to NSAC

July 17, 2001

Dr. T. James Symons
Chairman
DOE/NSF Nuclear Science Advisory Committee
Nuclear Science Division
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

Dear Dr. Symons:

Although the Nuclear Science Advisory Committee (NSAC) is currently in the midst of the development of its new long-range plan, the major findings and recommendations have already been conveyed to us in your briefings and have provided valuable guidance that is being incorporated into our planning. These recommendations address opportunities for significant scientific progress that can be realized by both effective use of existing capabilities and investments in new initiatives.

Further guidance is requested at this time by the Department of Energy (DOE) Nuclear Physics program in the implementation of these recommendations for its program in one of the major areas of nuclear physics research, namely nuclear structure and astrophysics studies. The future roles of its existing facilities in the Nation's nuclear structure and astrophysics research program need to be assessed in the context of the new capabilities in the United States and elsewhere. In the long-range planning exercise, the need for a facility such as the proposed Rare Isotope Accelerator (RIA), with next generation capabilities for exotic beams, was reaffirmed as important for addressing the forefront scientific questions. The priority of continued investments in the pursuit of this new facility in the context of a strategic plan for this subfield of nuclear physics needs to be determined. It is important that the available resources are directed to optimize DOE efforts, in coordination with the Nuclear Physics program at the National Science Foundation (NSF), for a strong national research program in this scientific area in the coming decade.

This letter requests that NSAC review and evaluate current and future scientific capabilities in the area of nuclear structure and astrophysics supported by the DOE Low Energy Nuclear Physics subprogram and make recommendations of priorities consistent with projected resources and the scientific opportunities identified in the new long-range plan.

The DOE program in nuclear structure and astrophysics supports operations and research at three national user facilities: ATLAS at Argonne National Laboratory, HRIBF at Oak Ridge National Laboratory, and the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory. Support is also provided for facility operations and research at four university Centers of Excellence at the Cyclotron Institute at Texas A&M University, the Triangle Universities Nuclear Laboratory at Duke University, the Center for Experimental Nuclear Physics and Astrophysics at the University of Washington, and the Wright Nuclear Structure Laboratory at Yale University. Funding is provided to university scientists and students for research at these facilities and elsewhere and for R&D activities at both national laboratories and universities in support of RIA.

In your examination of these facilities and research activities, please respond to the following questions:

> What scientific opportunities should be addressed and what facility and instrumentation capabilities should be used and developed, including those supported by NSF and outside the United States, in order to maintain a strong scientific program in the coming decade?
>
> What opportunities can be pursued with funding at the FY 2002 Budget Request level ($52.7 million) and an assumed constant level of effort into the outyears? What is the appropriate mix of facility operations, research, investments in instrumentation and RIA R&D that will be needed to optimally exploit these opportunities?
>
> What are the priorities of the scientific opportunities that could be pursued with additional funds beyond this constant level of effort?

We request that an interim report be given to DOE by November 15, 2001, and a written report responsive to this charge be provided by December 15, 2001.

Sincerely,

| | |
|---|---|
| James F. Decker | Robert A. Eisenstein |
| Acting Director | Assistant Director |
| Office of Science | Mathematical and Physical Sciences |
| Department of Energy | National Science Foundation |

bcc:
Brad Keister, NSF
SC-20

## B Charge to the Subcommittee

August 20, 2001

Professor Bradley Filippone
Kellogg Radiation Laboratory
California Institute of Technology
1200 East California Boulevard
Pasadena, California 91125

Dear Professor Filippone:

In a letter dated July 17, 2001, from James Decker and Robert Eisenstein, the Nuclear Science Advisory Committee (NSAC) has been charged to review the Department of Energy (DOE) program in one of the major areas of nuclear physics research, namely nuclear structure and astrophysics studies, and to provide guidance on a number of significant issues facing this program.

NSAC met on July 23, 2001 to discuss this request. Following discussion with representatives from the agencies, NSAC is establishing a Subcommittee on DOE Sponsored Nuclear Structure and Nuclear Astrophysics. This Subcommittee will be responsible for preparing a detailed analysis of the capabilities of the DOE nuclear structure and nuclear astrophysics programs and a set of recommendations responding to the charge.

Members of the Committee are:

| | |
|---|---|
| Bradley Filippone | Caltech, Chair |
| Juha Aysto | Jyvaskula and CERN |
| Lawrence Cardman | TJNAF |
| Vijay Pandharipande | University of Illinois, Urbana/Champagne |
| Mark Riley | Florida State University |
| Gene Sprouse | SUNY, Stony Brook |
| Michael Wiescher | Notre Dame University |
| Victor Viola | Indiana University |

The agencies prepared the charge with considerable care and I ask the Subcommittee to use the Decker/Eisenstein letter as the primary guide for its activities. In particular, I would ask the subcommittee provide careful answers in its written report to each of the questions posed on the second page of the letter. I would also like to make a few remarks, from my perspective, on the relationship between the Subcommittee's activities and the Long-Range Plan for Nuclear Science, which NSAC is currently preparing.

As you are aware, the NSAC Long Range Plan Working Group has drafted four prioritized recommendations on budgets. In its first recommendation, the working group recommends that the program be funded with adequate resources for effective operation of its recently constructed facilities, for university research groups and for the nuclear theory program. In the second recommendation, NSAC gives the highest priority for new construction to the Rare Isotope Accelerator (RIA) while maintaining the strength of the ongoing program at our new facilities. The desire to follow these two recommendations in a time of constrained budgets is one of the principal factors, which has led to this current review.

The Long-Range Plan Recommendations have been reached after a long process within the Nuclear Science Community and represent broad consensus among all the sub-fields of nuclear science. I expect the Subcommittee to be mindful of these priorities as it prepares its recommendations. Nevertheless, it is clear that the Subcommittee will develop a unique perspective of the DOE programs in nuclear structure and astrophysics over the coming weeks: both the strengths of individual programs, and the overall standing of the program relative to other capabilities in the US and the rest of the world. It should also be noted that the budget constraints presented to the Subcommittee are somewhat different from those provided to NSAC for preparation of the Long-Range Plan. Ultimately you must follow your own best judgement in preparing your recommendations to NSAC on this specific charge, taking into account the LRP recommendations and the capabilities of the program as you find them.

NSAC has been asked to provide a final written report by December 15, 2001. In order for NSAC to have time to meet and consider its response to the Agencies, the Subcommittee is asked to submit a written report of its findings and recommendations by November 15, 2001.

On behalf of the Nuclear Science Advisory Committee, I wish to thank all the members of the Subcommittee for their willingness to undertake this arduous, but very important, task.

Yours sincerely,

James Symons, Chair
DOE/NSF Nuclear Science Advisory Committee

c. J. Decker
R. Eisenstein
S.P. Rosen
J. Dehmer
D. Kovar
B. Keister

# C Subcommittee Membership

Juha Aysto
CERN
phone: +41-22-7675825
fax:
Juha.Aysto@cern.ch

Larry Cardman
JLAB
phone: (757) 269-5800
fax: (757) 269-7032
cardman@jlab.org

Brad Filippone
Caltech
phone: (626) 395-4517
fax: (626) 564-8708
brad@krl.caltech.edu

Vijay Pandharipande
Univ. Illinois-Urbana
phone: (217) 333-8079
fax: (217) 333-9819
vijay@rsm1.physics.uiuc.edu

Mark Riley
Florida State
phone: (850) 644-2066
fax: (850) 644-8630
mriley@nucott.physics.fsu.edu

Gene Sprouse
Stonybrook
phone: (631) 632-8118
fax:
Gene.Sprouse@sunysb.edu

Vic Viola
Univ. Indiana
phone: (812) 855-6537
fax: (812) 855-6645
viola@indiana.edu

Michael Wiescher
Notre Dame
phone: (219) 631-6788
fax: (219) 631-5952
Michael.C.Wiescher.1@nd.edu

# D Presentation Agendas

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Thurs. (9/6)
    BNL (Brookhaven Center - South Room)
        8:00  - 9:00  Executive session
        9:00  - 10:00 TAMU presentation         - Joe Natowitz
        10:00 - 10:30 Questions
        10:30 - 10:45 Coffee
        10:45 - 11:45 TUNL presentation         - Werner Tornow
        11:45 - 12:15 Questions
        12:15 - 1:00  Executive lunch
        1:00  - 2:00  UW presentation           - John Wilkerson
        2:00  - 2:30  Questions
        2:30  - 2:45  Coffee
        2:45  - 3:45  Yale presentation         - Rick Casten
        3:45  - 4:15  Questions
        4:15  - 4:45  Summary of other DOE LEP  - Gene Henry
        4:50  - 5:00  Gammasphere Update        - Sam Tabor
        5:00  - 5:45  Gamma-Ray Tracking Initiative
              Science                           - Thomas Glasmacher
              R&D, Status and Plans             - I-Yang Lee
        6:00  - 7:00  Executive session

Fri.   (9/7)
    BNL (Brookhaven Center - South Room)
        8:00  - 10:00 RIA Initiative
              Science: Nuclear Structure        - Witek Nazarewicz
                       Nuclear Astrophysics     - Hendrik Schatz
              Accelerator                       - Brad Sherrill
              RIA R&D Plan                      - Jerry Nolen
        10:30 - 10:45 Coffee Break
        10:45 - 11:15 FSU presentation
        11:20 - 11:50 Notre Dame presentation
        11:55 - 12:45 Exec lunch
        12:45 - 1:15  Stonybrook presentation
        1:20  - 2:20  MSU presentation
        2:45  - 4:30  Executive session
        4:30 Travel to ANL
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Draft agenda (24 Aug 01 version) ANL visit - NSAC Low Energy Program Review
see http://www.krl.caltech.edu/nsac.html for review charge and details.

September 8: All meetings in Building 203, R150

| | | | |
|---|---|---|---|
| 8:00 | Executive Breakfast | | |
| 8:30 | Welcome | | |
| 8:35 | Japanese Perspective | 40 | Tanihata |
| 9:15 | Executive Session | | |
| 9:30 | Introduction | 20+10 | Geesaman |
| 10:00 | Research Overview | 25+10 | Lister |
| 10:35 | Coffee | | |
| 10:45 | Heavy Elements and far from stability | 15+10 | Khoo |
| 11:10 | Proton Decay | 10+5 | Davids |
| 11:25 | CPT/APT | 15+10 | Savard |
| 11:50 | Nuclear Astro/Unstable beams | 20+10 | Rehm |
| 12:20 | ANL Users/ Users perspective | 10+5 | Cizewski |
| 12:35- | Executive Lunch | | |
| 1:40 | ATLAS Introduction | 25+10 | Nolen |
| 2:15 | Facility Tour<br>Coffee at end | 60 | 2/3 groups |
| 3:15 | ATLAS Budgets | 15+15 | Nolen |
| 3:45 | New Directions | 35+15 | Janssens |
| 4:35 | Coffee | | |
| 4:45 | RIA Overview and Science | 20+5 | Savard |
| 5:10 | RIA R&D | 20+10 | Nolen |
| 5:40 | RIA Plan | 10+10 | Geesaman |
| 6:00 | Executive Session | | |
| 7:00 | Dinner at Guest House | | |

September 9: All meetings in ANL Guest House unless committee prefers 203.

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|---|---|---|---|
| 7:30 | Executive Breakfast | | |
| 8:30 | ANL Wrap-up | 15+15 | Geesaman |
| 9:00 | Executive Session | | |
| 11:00 | Close out with PHY management | | |

ORNL Physics Division Low Energy Program Review Agenda

| Topic | Speaker | Time |
|---|---|---|
| September 10, 2001 | | |
| Executive Session | | 8:00-8:30 |
| Welcome | Roberto | 8:30-835 |
| Overview Presentations | | 8:35-10:00 |
| Low Energy Program | Bertrand | |
| Science Overview | Nazarewicz | |
| Facility Overview | Beene | |
| Facility Tour | Auble | 10:00-12:00 |
| Lunch | Committee with Facility Users | 12:00-1:00 |
| HRIBF Users | | 1:10-1:40 |
| User Program | Nazarewicz | |
| Division Low Energy Research Selected Topics | | 1:45-5:05 |
| L.E. Research Overview | Baktash | |
| Neutron-rich beams | Radford | |
| Astrophysics program | Smith | |
| Break | | |
| Studies around the proton drip line | Rykaczewski | |
| Reactions with RIB | Galindo-Uribarri | |
| Theory Connection | Dean | |
| HRIBF & RIA R&D Selected Topics | | 5:05-6:00 |
| Target/Ion Source Dev. | Alton | |
| Beam Development | Stracener | |
| Committee Executive Session Dinner Garden Plaza Hotel | | 7:00-10:00 |
| | | |
| September 11 | | |
| Executive Session Breakfast | | 7:30-8:00 |
| HRIBF & RIA R&D Selected Topics (continued) | | 8:00-8:25 |
| Research apparatus | Baktash | |
| HRIBF Future | Beene/Tatum | |
| Executive Session | | 9:00-11:00 |
| Executive Session Lunch with Management | | 11:00-11:45 |
| Committee Departs for airport | | 12:00 |

NSAC Review of Low-energy Nuclear Physics Program at LBNL Friday September 28, Building 50A, room 5132

8:00 Breakfast, executive session
9:00 Closed session (with C. Shank, L. Schroeder, and UC reps)

Overviews

9:30 NSD Perspective (L. Schroeder)
9:45 Introduction (S. Freedman)
10:15 Overview of Scientific Program (I. Y. Lee)
11:05 Break
11:15 ECR Development and Cyclotron Operation (C. Lyneis)
11:50 Cyclotron upgrades and opportunities (D. Wutte)

Scientific Highlights and Future Opportunities

12:05 Heavy element physics and chemistry (H. Nitsche)
12:35 Lunch in 50A-5132 (Committee and users)
1:35 Cyclotron tour

Scientific Highlights and Future Opportunities (cont.)

2:45 Nuclear structure (P. Fallon)
3:30 Aspects of Gammasphere physics with auxiliary detectors (D. Sarantites)
3:55 Liquid-gas phase transition (L. Phair)
4:25 Break
4:40 High precision measurements of weak interactions at 88 (P. Vetter)
5:10 Opportunities with radioactive beams at 88 (J. Cerny)
5:30 Executive session
6:30 Poster session in Cafeteria
7:30 Dinner in Perseverance Hall

Saturday, September 29 in Building 50A, room 5132

7:30 Breakfast, executive session Closing Statements
8:00 Summary (S. Freedman)

Other Facilities

8:45 TRIUMF Presentation (A. Shotter)

Executive Sessions

9:45 Executive session
11:30 Executive session with LBNL management
12:30 Working lunch: Final Executive Meeting
2:00 To be determined by the committee